# IRRIGATION CANAL SIMULATION MODELS AND ITS APPLICATION TO LARGE SCALE IRRIGATION SCHEMES IN SOUTH AFRICA

## A REVIEW

[a]George M. Ochieng, Olumuyiwa I. Ojo[a] and Fred. O. A. Otieno[b]
[a]Tshwane University of Technology, South Africa.
[b]Durban University of Technology, South Africa.
[a]Corresponding author: ochienggmm@tut.ac.za

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***Abstract:*** Irrigation Canal Simulation Model (ICSM) is a management and diagnostic tool in water management of open canal irrigation schemes. It is being adopted for efficient water management in large irrigation schemes in developed countries. The basic components of ICSMs and their development were reviewed with the focus of presenting their principles and procedures. The key issues on how to simulate water flow in irrigation canal and the prevailing conditions that can allow such issues to be studied and quantified were analysed and linked with the requirements and practical uses of the ICSMs. The applicability of such tool to the South Africa irrigation schemes was also assessed. The need for the experts to be drawn from research institutions like Dept. of Water & Environment, Council for Scientific and Industrial Research (CSIR), Agricultural Research Council (ARC) and Universities to initiate the process of developing a friendly ICSM was suggested, as this will help in the management of the schemes judging from the enormous cost investments. The cost effectiveness in terms of time, energy, human and materials resources savings are among the advantages for their adoption.

***Keywords*:** Hydraulic modelling. Irrigation Canal, Simulation Models

### I. INTRODUCTION

Irrigation Canal Simulation Models (ICSMs) have become useful and powerful tools for improving efficiency of irrigation water management practices especially at main and secondary Canals system levels. Higher efficiency often translates into increase in command area and 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 management scenarios. Most models combine efficient numerical algorithms and up-to-date user-friendly interfaces and are developed in close collaboration with the engineers and irrigation managers. It has been already used in many different countries: France, Sri Lanka, Pakistan, Burkina Faso, Mexico, Jordan, Senegal, etc. [1].

ICSM usage requires serious investments of time and personnel. Many excellent models are available, although very few can be considered user-friendly for the average design engineer. Canal models can simulate an actual canal, but the user must input the necessary canal gate-control algorithms in order to study the effects of various types of automation and control.

Use of ICSMs assists 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 schemes established are not normally operated as per design due to: change of crop pattern, introduction of a new water demanding crop or change in policy which may lead to higher scheme water demand. The alternative is physical redesign and constructions leading to additional investment which often overweigh the cost of acquiring or developing an ICSM.

Thus, ICSMs are representations 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, use of different cropping pattern and crop diversification, and to test new operational rules in the schemes.

In South Africa, there are several large irrigation projects used mainly for irrigation. The conveyance and distribution networks of the projects consist of open canals under manual control. They have been designed to serve large irrigation areas in accordance with collective land use requirements. Nowadays the operational conditions are changed and the irrigation projects exist with problems of inequitable water distribution and high operational losses. The need for improved management of the old canals is recognized and thus provides a good opportunity for the adaptation of ICSMs. The paper reviewed the development approach of ICSMs based on key issues and 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 South African (SA) irrigation schemes. Finally, the paper highlighted the existing limitations that would inhibit the adoption of foreign-based ICSMs in SA and argued that local expertise must be exploited to initiate such endeavour.

## II. THE REASONS FOR THE USE

Burt and Gartrell [1] highlighted several uses of ICSM models:

1. *Real time control*: A simulation program should not be used for real-time control when the actual canal is already providing the correct, actual data and the simulation program can never exactly predict the flows or water levels because the input data is always imprecise.

2. *Development of control algorithms and operational strategies*: This is where these models can excel. It is simply impossible to run hundreds of trials on a real canal and have access to all the desired data, but with a simulation model those trials can be done quickly and safely, with full access to all data.

3. *Canal design*: Often the canal design only solves for dimensions at maximum (steady) flow rates. If the canal design is completed in conjunction with a study of various advanced gate-control logics, the use of an unsteady model can pinpoint the needs for extra pool storage and freeboard.

4. *Studies of when to release water from a dam to a canal with upstream control*: Unsteady models can show how a flow rate and water-level changes pass through a canal system, with static or dynamic control structures.

5. *Studies of buffer reservoir operation in canal networks, or studies related to buffer reservoir design*: This may be another good potential use for the future generation of models.

## III. DEVELOPMENT APPROACH OF ICSMS

The flow of water in open channels of irrigation system varies spatially (steady state conditions) and sometimes both spatially and temporally (unsteady sate condition). The two real-life conditions exist whenever open channels are being used to convey water. 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 an 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". The two major issues, therefore, in simulating flow of irrigation water in a canal which can deliver water in accurate and flexible way are,

(a) The mathematical concept (equation) that can represent hydraulics of water flow in open canals in steady and unsteady conditions

(b) 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 processes assumed in ICSMs while the second issue can be presented under water level control function.

## IV. EQUATIONS GOVERNING WATER FLOW IN OPEN CHANEL

### *UNSTEADY FLOW CONDITIONS*

This situation arises when water is suddenly released from upstream off-take at high elevation through a gate opening to an open canal at lower elevation until the flow becomes steady. The governing equations used for simulating gradually varied one dimensional unsteady flow equation are usually the "Saint Venant equations". The equations were derived from laws of conservation of momentum and mass. Amanda [2] presented a detailed method for deriving these equations. The Q and A form of the equations are: [3]:

Momentum Equation:

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

Continuity Equation:

$$\frac{\partial h}{\partial t} + \frac{1}{B}\frac{\partial Q}{\partial x} = q \qquad [2]$$

There are other forms of saint venant equations in literature [2]. 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 condition at such locations is described by the equation of mass and energy conservation [4]. Assuming no change in storage volume at the junction, the continuity equation can be stated as:

$$\sum Q_i = \sum Q_o \qquad [3]$$

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

### *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. The steady state equation of water flow using equations 1 and 2 after neglecting the time derivatives can thus be derived [4]. Misra [5] faulted the use of gradually varied flow equation given by Chow [6] 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 varying significantly different from the designed ones. Therefore, he modified the spatially varied equations and expressed them as:

$$\frac{dQ}{dx} = q_s + Q_L \delta(x - x_L) \qquad [4]$$

$$\frac{dh}{dx} = \frac{S_o - S_f - \frac{2\beta Q}{gA^2}(q_s + Q_L \delta(x - x_L))}{1 - \beta \frac{Q^2 B}{gA^3}} \qquad [5]$$

Where $Q_L$ = turn out discharge, β = momentum correction factor which is taken as unity, $\delta(x\text{-}x_L)$ =dirac delta function, $x_L$ = location of the turnout, $q_s$ = rate of seepage per unit length, $q_s$ can be obtained from Wachyan and Ruston [7] as:

$$q_s = Kp \qquad [6]$$

Where K = seepage coefficient, p = wetted perimeter. $Q_L$ is given by Tod *et al* [8].

$$Q_L = \sqrt{\frac{2g}{K_L}} A_L w_L \sqrt{h - Z_L} \qquad [7]$$

Where $K_L$ = total energy loss coefficient with value of 2.5 given by Misra [5]. $A_L$= Area of turn output $W_L$ = ratio of turn out opening to turn out area, $Z_L$= downstream reference level.

The initial stage of developing ICSMs is solving equations (1) to (7). The task of solving these equations required high mathematical skills and good knowledge of computer programming as equations 1, 2, 5, 6, and 7 respectively have no analytical solutions. There exist only numerical solutions for the equations [4, 9, 10, 11, and 12]. The unsteady flow condition normally lasts for a very short duration in the canal system but the condition posses more complex challenges to researchers in finding accurate solutions. Broadly, there exist four approaches to the solutions of unsteady flow (Saint-Venant) equations. Namely; method of characteristics, finite difference method, finite volume method and finite–element method [2,5,13].

In the method of characteristics, the equations are first converted into characteristic form and then solved by finite–difference scheme. Although this method was popular in the 1960s but the method is not suitable for systems having numerous geometrical changes and it fails because of the convergence of the characteristic curve whenever there is wave shock/bore [14]. 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 consists of two methods; explicit finite–difference and implicit finite-difference methods. In the former method, the partial derivatives of the two equations 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 [14]. Although, this method is simple to use compared to the later method. Its stability depend heavily on the following "courant" condition given as: [14].

$$\Delta t \le \frac{\Delta x}{V \pm C} \qquad [8]$$

Where Δt = time step Δx = distance step, V= average flow velocity C= wave celerity. Strelkoff [15] cautioned that the 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 uses backward 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 the shorter computer time requirement as there are 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.

Recent developments in the use of implicit methods have greatly improved the accuracy and reliability of ICSMs. The use of Preissmen's method for descritization of x-t plane and using double sweep or iterative Newton methods of solving the Saint Venant equations adopted by Mishra [5], Kumar et al [16] and Mishra [12] among others is such development. The solutions of these equations are arrived at with the use of initial and boundary conditions as indicated by Chaudhry [14]. The initial conditions are determined from solving the steady state conditions in which the solved unknowns becomes initial values of subsequent computations

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 criteria are accuracy, consistency, stability and convergence. In theory the criteria were used in formulating the different methods but in reality, there may be some differences. The method of testing a suitable approach using above criteria were explained by Amanda [2].

## V. WATER LEVEL CONTROL FUNCTION

In general, the water level control function is part of the requirement for solving the Saint Venant equations. It involves the choice of the boundary conditions at the off-take gates for diversion or cross regulators or functions. There are four common boundary conditions encountered in typical irrigation canal systems [14]:

*a.* Constant water level at upstream gates/regulators
*b.* Constant water level at down stream
*c.* Variable discharge at upstream/downstream end
*d.* Conditions a-b at junction of two or more channels

The manipulations of these boundary conditions give rise to three types of control algorithms; feedback 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 [17] while examples can be found in [18]. Feed forward control algorithm is sometimes called gate stroking where the computed action variables are compared with the set values of the variables. Example of feed forward control could be found in [19] and [20]. 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. Examples are available in [21, 22].

The ICSMs can be developed for application in most typical open canal irrigation system through the process described in preceding sections. There are also several software available for use. Some of the available canal hydraulic models software 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 an irrigation scheme. Existing simulation models have their positive and negative aspects. The positive aspect is the interest in such models and their usage also model programs are becoming more widely available for use on Personal Computers (PC) and lastly some effective modeling programs exist. The negative part is that these computer programs are not comparable to standard user-friendly PC software. Unsteady canal models with virtually no documentation can provide a very frustrating experience. Canal models, as a rule, have insufficient documentation, require extensive knowledge of programming and hydraulics are cumbersome to manipulate and operate, and have generally been developed for some special circumstance that differs from the new application in just enough ways to be troublesome [1].

## VI. REQUIREMENTS OF ICSMS

In order to use ICMSs for a given canal; it is necessary to have physical and hydraulic data [3]. 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 reasonably close.

## VII. ADVANTAGES OF ICSMS

ICSMs can give results of the simulation process both in graphical and tabular forms. Water depths and discharges in every section of the simulated canal are provided for a given control action (gate opening, position and opening duration). The results provide for 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 (wave) reaches each section of the canal. The time at which steady state condition is achieved at different sections of the canal can also be monitored. The canal managers can develop effective operation rules that minimize water and energy wastages, and allow only a safe discharge to flow in the canal thereby maximizing efficient use of water and prolonging the canal life span. The managers can also create and test new scenarios using computer simulation. Such new scenarios could be change of cropping pattern, new irrigation schedules, introduction of more/less water demanding crops and increasing crop diversity. ICSMs could assist managers to identify potential emergency operational problems for early intervention.

## VIII. RELEVANCE OF ICSMS TO LARGE IRRIGATION SCHEMES

Irrigation schemes were established to boost food production. Some of the schemes were constructed without adequate testing and necessary modifications to the design. Issues of compatibility with technical expertise and environmental conditions among others were over looked. Table in the appendix lists some irrigation schemes in South Africa. The causes of the constraints and low performance are many among which are shortage of qualified and experienced staff, insufficient funds for scheme operation and maintenance and insufficient or lack of working materials. There is neither time nor resources to embark on total elimination of these constraints through the conventional way of redesign; award of contract, modification, testing and certification, thus the utilization of ICSMs is promising in the prevailing situation.

## IX. SUMMARY AND CONCLUSION

The introduction of the ICSMs to South African irrigation schemes may help in addressing operation and maintenance problems. They are valuable aids in development, design and redesign, but they require firm and considerable commitment of time and personnel. Most are not yet considered to be user-friendly for the average engineer. It is expedient and effective to initiate the process of developing a simulation model that can accommodate the level of deterioration of the irrigation schemes in the country. This calls for team work by all experts working in this area. It requires both institutional and personal linkages between Department of Water Affairs, research institutions like CSIR, universities and organizations and experts in selected learning and research centres in developed countries.

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