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Simulation modelling in surface irrigation systems

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Abstract— **Australia is one of the driest countries in the world and hence irrigation, and particularly surface irrigation, is a significant agricultural activity. In the recent past, efforts have been made towards devising strategies necessary for efficient use of water. The desire to optimise the dollar output of this scarce resource while at the same time conserving the environment is the main motivation for these efforts.**

Computer simulation models have the potential to improve the efficiency of irrigation systems and thus deliver significant water savings. This can be achieved by optimising the design and management decisions at the field level. The purpose of this paper is to review the simulation models that have been developed for surface irrigation. The impacts of these models in the irrigation industry in Australia as well as their limitations are also discussed.

In the majority of the surface irrigation simulation models currently in use, previous field characteristics are used to optimise future irrigations. However, numerous researchers have established that these characteristics change both with time and space, and hence the accuracy of such models may be affected. A conceptual design of a computer simulation model suitable for use in automated furrow systems utilising adaptive real time control is presented. This is part of an on-going research project at USQ aimed at modernising the furrow system.

Keywords **Simulation modelling, real-time control, surface irrigation**

I. INTRODUCTION

Surface irrigation refers to application systems in which water is applied and conveyed over the field surface by gravitational force. Furrow, border and basin systems are the most common configurations of surface irrigation. Surface systems are by far the most widely used for the irrigation of crops and pasture in the world, and account for about 63% of the total irrigated land in Australia (ABS 2010).

Simulation in surface systems is the process of mathematically describing the hydraulic characteristics of water as it flows from one end of the field to the other. This is achieved by use of computer models based on mathematical equations known as Saint Venant equations. SIRMOD (Walker 1997) and WinSRFR (Bautista et al. 2009 appear to be the most widely used simulation models in Australia and US respectively. SIRMOD has particularly been embraced in the cotton industry in Australia and has become a standard evaluation tool (Gillies 2008).

There is a large amount of published literature focussing on the potential benefits of applying simulation modelling during the design and management stages of surface irrigation systems. They report increased water use efficiency as a key benefit of modelling leading to large water savings. For instance the BDA group (2007) cited in Smith et al. (2009) estimate water savings in the cotton industry of 400 GL over a 16 year period corresponding to an increase in water use efficiency of 10%.

This paper reviews the common surface irrigation simulation models and their impact in the irrigation industry in Australia. These models however rely on soil infiltration data from previous irrigations to predict the performance of future irrigations, thereby ignoring the temporal variation in infiltration. A simulation model is being developed at USQ as part of an on-going project aimed at modernising the furrow system. The software to be used in automated furrow systems utilises adaptive real time control concept. This is expected to overcome the problem of variability of soil infiltration characteristics. The conceptual design of the model is presented.

II. BACKGROUND TO SIMULATION MODELLING IN SURFACE SYSTEMS

A. *Purpose of simulation*

Surface irrigation simulation models are useful tools both at the design and management stages of the surface systems. When used for irrigation design purposes, simulation models help to optimise surface irrigation variables such as field slope, length of the field and the design flow rate. That is, the models can aid the designer in making decisions as to the appropriate values of these variables that produce the best performance. This is mostly applicable to newly established fields or when converting to surface system from a different application method. These variables (particularly field slope and length) are difficult or expensive to vary once the system is operational.

Time to inflow cut-off, inflow rate and the desired depth of application are management decisions that can be optimised using simulation models. This is often preceded by a field evaluation process to generate the data to be used by the simulation model. The optimised variables are used to modify future irrigations in order to achieve the desired level of performance.

Whether used for design or management purposes, simulation modelling provides an opportunity to identify and evaluate more efficient practices at a lower cost and shorter time compared to field trials (Raine and Walker 1998).

B. *Governing equations*

In surface irrigation, water flows along the surface as it infiltrates into the soil profile. Due to the variability of soil intake rates (Walker 1989), the flow is both spatially varied and unsteady (Walker and Skogerboe 1987). This condition is hydraulically similar to unsteady open channel flow and thus can be described by Saint Venant equations. These equations are based on the principle of conservation of mass or continuity (Eqn. 1) and motion or momentum (Eqn. 2).

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} + I_x = 0 \qquad (1)$$

$$\frac{I}{g}\frac{\partial V}{\partial t} + \frac{V}{g}\frac{\partial V}{\partial x} + \frac{\partial y}{\partial x} = S_o - S_f + \frac{I_x V}{gA} \qquad (2)$$

where Q is the discharge (m^3/s), A is the cross-sectional area of flow (m^2) at a depth of y (m), x is the distance along the furrow (m), t is the time (s) I is the infiltration rate ($m^3/m/s$), g is gravitational acceleration (m/s^2), V is the velocity of flow (m/s), S_o is the channel bottom slope and S_f is the channel friction slope. These are the basic mathematical equations used by surface irrigation simulation models to simulate the physical and hydraulic characteristics of an irrigation event.

Due to the complexity of the above equations (McClymont 2007), no analytical solution to the complete equations has been found. Models that have been used for the solution of these equations fall into one of the following four major categories: complete hydrodynamic models, zero inertia models, kinematic wave models and the volume balance models. The complete hydrodynamic models use the complete form of the Saint Venant equations and are therefore the most accurate, but also the most complex. The other three models use simplified forms of the Saint Venant equations. In this case the solution is an approximation of reality, but is quicker compared to the full set of the Saint Venant equations. The volume balance models only use the continuity equation (Eqn. 1) as it is the dominant of the two equations (Raine and Smith 2007) and is the simplest approximation of the Saint Venant equations (McClymont 2007).

C. *Soil infiltration characteristic*

The rate of flow of water along the surface is affected by the magnitude of infiltration or entry of water into the soil profile. The higher the infiltration rate, the slower the advance of water down the bay or furrow and rapid recession. The infiltration characteristic of the soil is therefore a key variable that determines the performance of a surface irrigation application system (Raine and Smith 2007). The most commonly used model to describe the soil infiltration characteristic for surface irrigation is the Kostiakov-Lewis equation:

$$I = k\tau^a + f_o\tau \qquad (3)$$

where I is the cumulative infiltration (m^3/m), τ is the time (min) from the commencement of infiltration, k ($m^3/min^a/m$) and a (non-dimensional) are fitted parameters and f_o ($m^3/min/m$) approximates the steady or final infiltration rate. Many surface irrigation simulation models incorporate the above infiltration model.

III. REVIEW OF EXISTING MODELS

The advent of the computer has led to development of a number of simulation models used for surface irrigation simulation and optimisation. SIRMOD (Walker 1997) and WinSRFR (Bautista et al. 2009), the successor of SRFR (Strelkoff et al. 1998), appear to be the most widely applied surface irrigation models in Australia and the US respectively. These and other models are summarised below:

A. *SIRMOD*

SIRMOD (surface irrigation simulation, evaluation and design) is a comprehensive simulation software package for simulating surface irrigation hydraulics. In Australia, SIRMOD, developed by Utah State University, has been widely accepted as the standard for the evaluation and optimisation of furrow irrigation (Gillies 2008) and can also be used to simulate basin and border irrigation (Gillies et al. 2008). The software is based on the full hydrodynamic model but is also capable of applying the volume balance model to determine the infiltration characteristics of an irrigated furrow from two points on the advance curve. Commonly the infiltration parameters are instead estimated outside SIRMOD using models such as IPARM (Gillies and Smith 2005).

SIRMOD version II is commercially available through IRRIMATE™ (a suite of hardware and software tools developed by the National Centre for Engineering in Agriculture, NCEA, based at the University of Southern Queensland). As a design tool, SIRMOD is used to predict the irrigation performance under alternative field parameters (length and slope). SIRMOD can also be used to identify performance improvements under different management practices.

SIRMOD main output screen (Fig. 1) includes a plot of the distribution of infiltrated water, simulated irrigation performance, volume balance and the runoff hydrograph.

B. *WinSRFR*

WinSRFR is the latest of a series of surface irrigation hydraulic simulation models developed by the USDA-Agricultural Research Service. It is an integration of the surface irrigation (basin, border and furrow) program SRFR, level basin design program BASIN (Clemmens et al. 1995) and sloping border-strip program BORDER (Strelkoff et al. 1996). This new program also contains additional features and is Windows based.

Unlike SIRMOD, WinSRFR employs simplified forms of the momentum equation (i.e., the zero-inertia or kinematic-wave models). This modelling technique has been found by USDA-ALARC (2009) to be sufficiently accurate when used under the right conditions and is also computationally faster. The program’s four hydraulic functionalities (known as WinSRFR Worlds) are event analysis, simulation, physical design and operational analysis (Fig. 2).

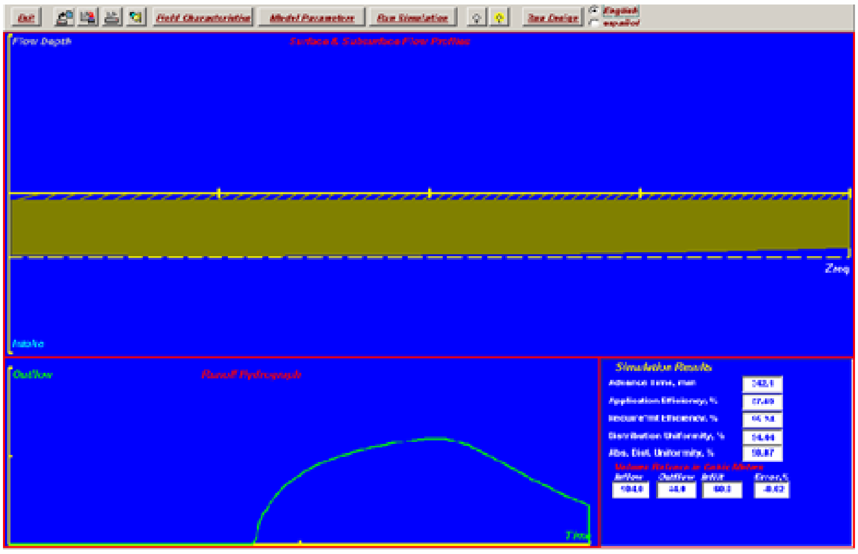

Figure 1. SIRMOD main input screen

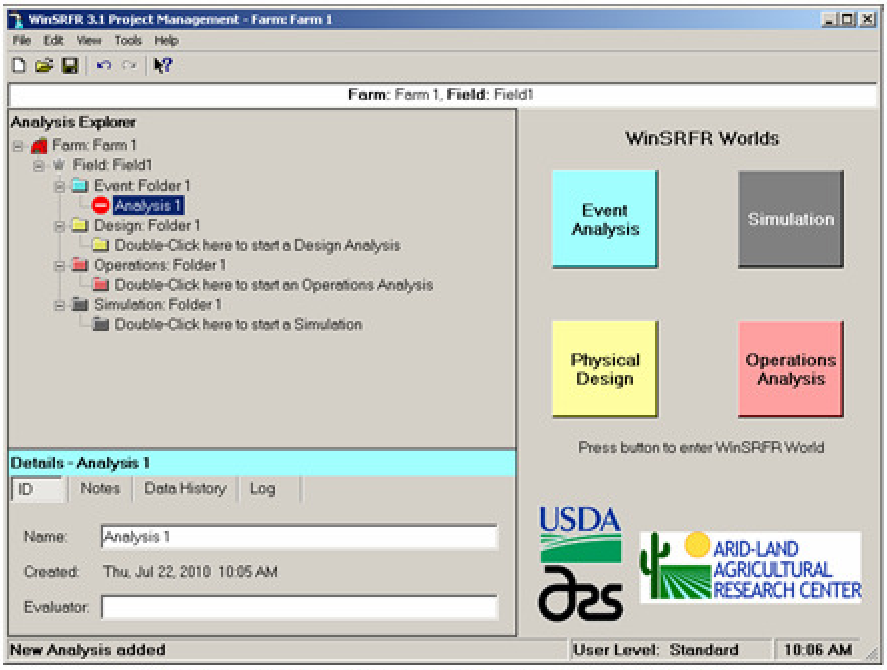

Figure 2. WinSRFR 3.1 Project Management window

The first function evaluates the performance of an irrigation event based on measured data and estimates the soil infiltration characteristics necessary for the simulation process. The simulation outputs include the advance and recession trajectories, flow and depth hydrographs and the final infiltration profile. The physical design function is used for the optimisation of the physical dimensions of the surface irrigation system while the operational analysis function is used to determine the best combination of the management practices (inflow and time to cut off).

WinSRFR 3.1 is downloadable from the internet free of charge (http://www.ars.usda.gov/services/software.htm). The software is used by researchers and farmers in the US, but there is little indication of its application in the Australian irrigation industry.

C. Recent Australian models

Development of improved simulation tools has long been the objective of the irrigation research at USQ. FIDO (McClymont et al. 1999) was an attempt to develop the complete furrow irrigation model, based on the full hydrodynamic equations, capable of parameterisation, simulation and optimisation. Never completed for commercial release it none-the-less provided the basis for:

- IrriProb (Gillies et al. 2008) which has the capability to simulate multiple furrows and optimise performance at the scale of the whole field, and

- SISCO (Gillies et al. 2010) which is the realisation of the FIDO objective for both furrow and bay systems.

SISCO as the basis for the real time simulation and control is discussed later in this paper.

An interesting attempt to find an analytic solution to the kinematic wave approximation resulted in the development of the AIM model (Austin and Prendergast 1997). Developed specifically for bay irrigation of cracking clay soils, AIM is simple to use but under certain conditions suffers from unacceptable inaccuracy. As a consequence adoption of AIM has been low. AIM was used recently in the IIC (intelligent irrigation controller) in a trial at an automated border-check farm in Dookie, Northern Victoria (Dassanayake et al. 2009). This is a relatively new development in surface irrigation, and there is no evidence of significant adoption at present.

IV. IMPACT OF SIMULATION MODELLING IN THE IRRIGATION INDUSTRY

A. *Overview*

Irrigation water is used in circumstances where rainwater is insufficient to satisfy the moisture requirements of plants. The primary goal of an irrigation application system is to uniformly supply the required amount of water which is often a difficult task in surface systems. The level of achievement of the goal of an irrigation application system is termed irrigation performance. Performance measures commonly used in surface irrigation are (i) application efficiency (AE) (ii) requirement efficiency (RE) and (iii) distribution uniformity (DU).

AE is a measure of the proportion of water made available for plant use during an irrigation process and is defined as:

$$AE = \frac{volume\ stored\ in\ the\ root\ zone}{volume\ appled} \tag{4}$$

RE is an indication of how well the water requirements have been met and is defined as:

$$RE = \frac{volume\ stored\ in\ the\ root\ zone}{deficit\ prior\ to\ irrigation} \tag{5}$$

DU is the measure of the evenness of water application across the field and is usually expressed as:

$$DU = \frac{average\ of\ the\ lowest\ 25\%\ of\ applied\ depths}{average\ depth\ applied\ over\ the\ whole\ field} \tag{6}$$

The main factors that impact on the performance of surface irrigation can be categorised as design, soil and management variables. Design variables include the longitudinal slope of the field which affects both the rate of advance and recession and the length of the furrow which determines the flow rate required. The infiltration characteristic of the soil determines the rate of infiltration of water into the soil and hence controls both the rate of advance and recession of water down the furrow or bay. The depth of application, furrow flow rate and time to cut off are management variables. In many cases, time to cut-off is the only quantity that can be varied to achieve a desired level of irrigation performance (Raine and Smith 2007).

B. *Sample simulation*

Data collected for an on-going project at USQ aimed at modernising furrow irrigation was used to illustrate simulation modelling in surface systems. The field sites were located at furrow-irrigated commercial cotton properties in Dalby and the Gwydir Valley (Table 1).

Two irrigation events were monitored at each site (G1 and G2 for the Gwydir and D1 and D2 for the Dalby trials sites). IRRIMATE^{TM} tools were used to measure the flow rates and monitor the advance of water down the furrow while the soil infiltration characteristics (Fig. 3) were estimated using IPARM (Gillies et al. 2005).

These infiltration characteristics were used in SIRMOD II to evaluate the performance of the irrigation events as per the usual management practices of the irrigators (Table 2). The irrigation deficits used in this illustration were estimated by the irrigators. The evaluation suggested that the AE for the four irrigation events ranged from 50.4 to 79.1 %. A volume of 1.04 ML/ha and 1.25 ML/ha were applied in the Gwydir Valley and Dalby trial sites respectively.

An investigation was then undertaken to evaluate the benefits of irrigation optimisation using SIRMOD II. In this case the strategy used was a reduction of inflow time while ensuring that the water reached the bottom end of the field. This clearly leads to an increase in the AE and a decrease of the RE and DU. A compromise was achieved by setting the lower limit of RE at 80%. In addition to the improved AE, the optimised results suggest water savings of 0.164 – 0.327 ML/ha (Table 3) were possible. There was also a reduction of runoff.

Table 1 Field characteristics

Site	Furrow geometry (m)					
	Top width	Middle width	Depth	Bottom width	Furrow length	Furrow slope (%)
Gwydir Valley	0.75	0.51	0.125	0.3	1000	0.1
Dalby	0.6	0.437	0.102	0.273	440	0.2

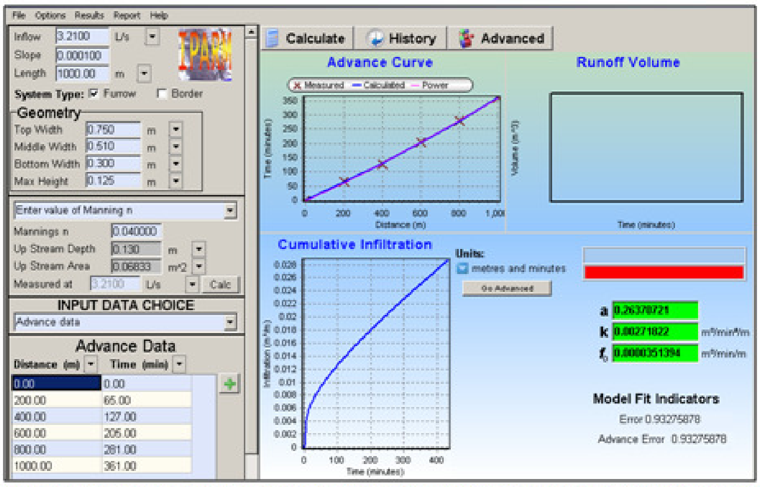

Figure 3 IPARM simulation showing infiltration characteristics for G2 in the Gwydir Valley

Table 2 Summary of measured irrigation performance characteristics

Site	Flow rate	Time to	Deficit	AE	RE	DU	Vol. applied	Run off
	(l/s)	cutoff (min)	(mm)	(%)	(%)	(%)	(ML/ha)	(ML/ha)
Gwydir Valley								
G1	3.21	540	60	57.7	85.7	94.6	1.04	0.440
G2	3.21	540	60	50.4	87.3	98.5	1.04	0.516
Dalby								
D1	2.7	680	100	79.1	99.0	83.7	1.25	0.083
D2	2.7	680	100	79.1	99.1	83.8	1.25	0.084

Table 3 Optimised irrigation performances

Site	Time to	AE	RE	DU	Vol. applied	Saving	Run off
	cutoff (min)	(%)	(%)	(%)	(ML/ha)	(ML/ha)	(ML/ha)
Gwydir Valley							
G1	370	67.9	80.7	93.1	0.713	0.327	0.228
G2	450	55.6	80.3	98.2	0.867	0.173	0.384
Dalby							
D1	590	88.0	95.6	75.5	1.086	0.164	0.00114
D2	590	88.1	95.7	75.7	1.086	0.164	0.00114

C. Previous studies

Published data detailing water savings and increased efficiency through farm redesign and change of management practices are summarised in Table 4.

V. PROPOSED REAL-TIME CONTROL SOFTWARE

A. Infiltration variability and real-time control

All the simulation models in surface irrigation including SIRMOD, WinSRFR, and SISCO use historical data to predict performance of future irrigations. However, infiltration characteristics of the soil in an irrigated field vary both with respect to time and space (for example Smith et. al. 2007; Gillies 2008; Walker 1989; Emilio et al. 1997).

Spatial variability is primarily attributable to the differences in the soil physical and chemical properties while temporal variability may be as a result of farming systems or moisture content differences. Infiltration variability causes non-uniformity in water absorption rates and furrow stream advance rates (Trout 1990). It follows that the soil infiltration characteristics obtained at any particular time of the season may not be adequate for use in the simulations to predict irrigation performance for later irrigations. To achieve the desired depth of application and uniformity, irrigators tend to increase the application times, often leading to deep drainage mostly in the upstream end of the field and runoff from the downstream end. Trout (1990) and Gillies (2008) concluded that infiltration variability significantly reduces irrigation water use efficiency.

Table 4 Published data on the benefits of simulation modelling

Source	Location	Application system	Simulation tool	Strategy used	Benefits
Raine and Shannon 1996	Burdekin River Delta	Furrow	SIRMOD	Decrease furrow length from 600 to 300m	Decrease of volume applied from 1.78 to 1.03 ML/ha/irrigation
Dassanayake et al. 2009	Dookie, Victoria	Border	Real Time Intelligent Irrigation Controller (ARTIIC)	Optimised cut off time	38% water saving over conventional irrigation
Langat and Raine 2006	Bura Irrigation Scheme, Kenya	Furrow	SIRMOD	Increased flow rate and optimised cut off time	Increased AE from 79.4 to 87.5%.
Raine et al. 2005	Queensland, New South Wales	Furrow	SIRMOD	Optimised siphon flow rates and time to cut off	Water saving of 0.15 ML/ha/irrigation
Smith et al. 2005	Southern Queensland	Furrow	SIRMOD	Increased flow rates, reduced inflow times	AE increased from average of 48% to 85-95%.
Montgomery and Wigginton 2008	Gwydir and Namoi Valley	Furrow	SIRMOD	Increased flow rates, reduced inflow times	Water saving of 0.18ML/ha/irrigation
Smith et al. 2009	Goulburn Murray Irrigation District (GMID)	Border	SIRMOD/SISCO	Shorter irrigation times and higher flow rates	Gain in AE of 19%
Gillies et al. 2010	GMID	Border	SIRMOD/SISCO/ IPARM	Doubling flow rate (from 0.132 to 0.268 ML/day/m).	Water savings of 0.256 ML/ha/irrigation (19% increase in AE).

Real-time control has been proposed for the management of temporal variability of infiltration characteristics (for example Emilio et al. 1997; Mailhol & Gonzalez 1993; Khatri & Smith 2006; Turral 1996). In this approach the infiltration characteristics are measured, analysed and used to make decisions for the current irrigation event. A simulation model suitable for real-time control of surface irrigation must be able to obtain infiltration estimates in the shortest time possible and use the results to optimise that particular irrigation event.

B. Model description

As part of an on-going project at USQ aimed at modernising the furrow system, a computer simulation model for adaptive real-time control is currently under development. Although the model is initially being developed for use in automated furrow systems, only minor modifications will be necessary before it can be applied in bay and basin irrigation systems. Gated layflat fluming with an automatic valve at the upstream end will be used to deliver water to individual furrows in the automated system. A pressure sensor will be attached to the layflat to give continuous inference of flow rate using the Gpipe program (Smith 1990). A water sensor placed midway down the furrow will send signals to the controller via telemetry.

A scaling technique proposed by Khatri and Smith (2006) will be used to reduce the amount of data required to acquire the infiltration characteristics of the soil. The approach assumes that the shape of the infiltration characteristic for a particular field or soil is relatively constant despite variations in magnitudes of the infiltration rate or depth of infiltration.

A representative furrow in the field is selected and evaluated over an irrigation event, and the model infiltration curve is obtained using the Kostiakov-Lewis equation. A scaling factor (F) is formulated for each furrow or event from a re-arrangement of the volume balance model (as used by Elliot and Walker (1982):

$$F = \frac{Q_o t - \sigma_y A_o x}{\sigma_z k t^a x + \dfrac{f_o t x}{1+r}} \tag{7}$$

where Q_o is the inflow rate for the corresponding furrow (m^3/min), A_o is the cross-sectional area of the flow at the upstream end of the field (m^2), t is the time (min) for the advance to reach the distance x (m) for the corresponding furrow, σ_y (dimensionless) is the surface storage shape factor, and σ_z (dimensionless) is the sub-surface shape factor and is defined as:

$$\sigma_z = \frac{a + r(1-a) + 1}{(1+a)(1+r)} \tag{8}$$

where r is the exponent from the power curve advance function $x = p(t)^r$ for the model furrow. The inflow rate will be inferred from the continuous pressure monitoring in the fluming. The scaling factor is then applied to the Kostiakov-Lewis equation to obtain the scaled infiltration curves for the whole field:

$$I_s = F(k\tau^a + f_o \tau) \tag{9}$$

where I_s is the scaled infiltration (m^3/m), a, k, f_o are the infiltration parameters of the model furrow. Only one advance point approximately midway down the furrow will be required in this process. The scaled infiltration characteristics obtained from this approach are then used in a simulation and optimisation process to determine the time to cut-off the inflow.

The proposed software uses the SISCO simulation engine which is based on the complete hydrodynamic equations and provides a suitable platform for computer programs founded on real time control concept. The simulations will be run over a range of feasible cut-off times. A user-defined optimisation routine will be used to determine the optimal time to cut off. The conceptual design of the new simulation model in presented in Fig. 4.

VI. CONCLUSIONS

Computer simulation modelling is used both for design and management purposes in surface irrigation systems. Simulation models help irrigators make informed decisions concerning their irrigation practices. SIRMOD and WinSRFR appear to be the most widely used simulation tools in Australia and the US respectively.

This paper has shown that there are prospects of increase in water use efficiency and water savings by using simulation modelling. Water savings of 400 GL and an increase in water use efficiency of 10% over a 16 year period in the cotton industry in Australia has been reported by BDA Group (2007).

The conceptual design of a simulation model being developed at USQ as part of an on-going project on furrow automation has been presented. The model utilises adaptive real time control concept and is expected to overcome the problem of soil infiltration temporal and spatial variability.

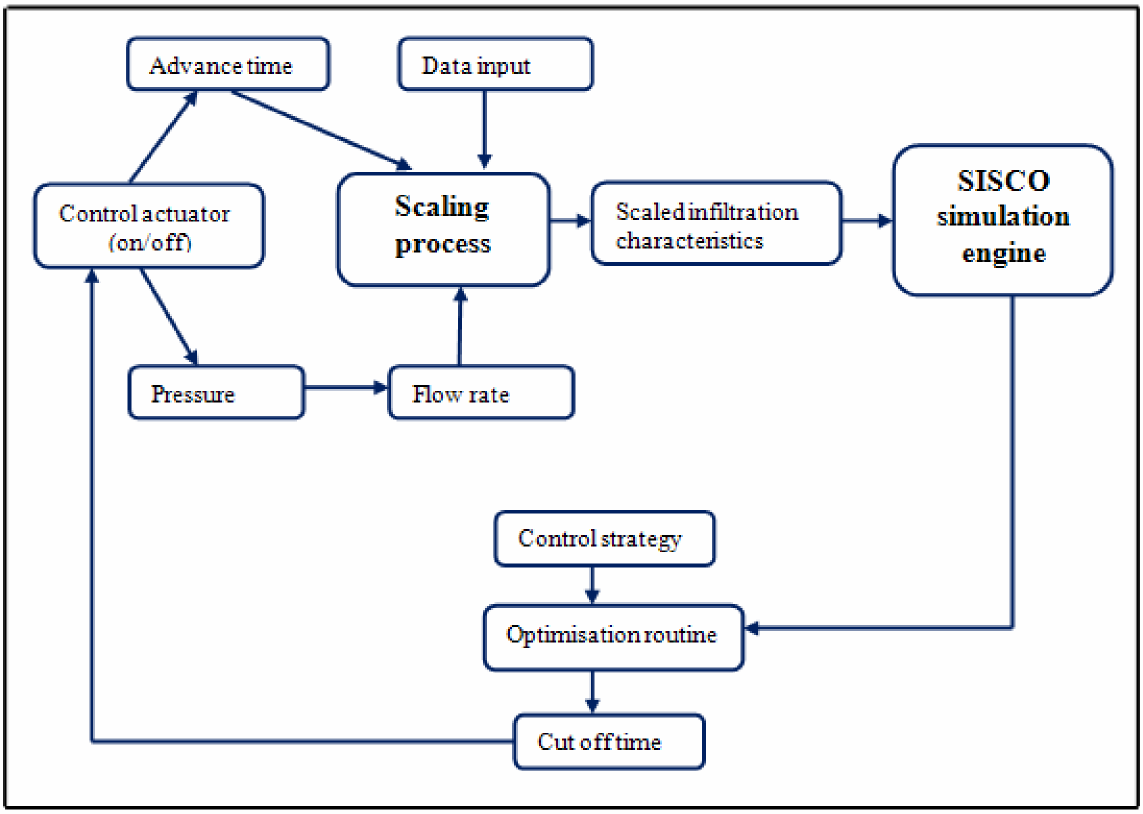

Figure 4. Conceptual design of real time control software

REFERENCES

[1] Austin, N. R & Prendergast, J. B 1997, 'Use of kinematic wave theory to model irrigation on cracking soil', Irrigation Science, vol. 18: 1–10.

[2] BDA Group 2007, 'Cost Benefit Analyses of Research Funded by the CRDC', Report to Cotton Research and Development Corporation, BDA Group, Manuka, ACT, Australia.

[3] Clemmens, A. J., Dedrick, A. R., Strand. R. J. 1995 'BASIN—a computer program for the design of level-basin irrigation systems, version 2.0', WCL Report 19. USDA-ARS U.S. Water Conservation Laboratory, Phoenix, AZ.

[4] Dassanayake, D., Dassanayake, K., Malano, H., Dunn, M., Douglas, P and Langford, L. 2009, 'Water saving through smarter irrigation in Australian dairy farming: Use of intelligent irrigation controller and wireless sensor network', 18th World IMACS / MODSIM Congress, Cairns, Australia 13-17 July 2009.

[5] Emilio, C., Carlos, P. L., Jose, R. C. & Miguel, A. 1997, 'IPE: Model for Management and Control of Furrow Irrigation in Real Time', Journal of Irrigation and Drainage Engineering, 123(4), 264-9.

[6] Gillies, M. H, Smith, R. J & Raine, S. R 2008, 'A review of Basin (Contour) Irrigation Systems II: Research needs for evaluation and design', CRC for Irrigation Futures Report, Irrigation Matters Series No. 01-2/08.

[7] Gillies, M. H, Smith, R. J, Williamson, B. and Shanahan, M. 2010, 'Improving performance of bay irrigation through higher flow rates', Australian Irrigation Conference and Exhibition 2010, Sydney, NSW, Australia, 8 -10 June 2010.

[8] Gillies, M. H. 2008, 'Managing the effect of infiltration variability on the performance of surface irrigation', PhD Thesis, University of Southern Queensland, Toowoomba.

[9] Gillies, M. H. and Smith, R. J. 2005, 'Infiltration parameters from surface irrigation advance and run-off data', Irrigation Science, 24(1), 25-35.

[10] Khatri, K. L & Smith, R. J 2006, 'Real-time prediction of soil infiltration characteristics for the management of furrow irrigation', Irrigation Science, 25(1), 33-43.

[11] Lam, Y. S., Wallender, W. and Upadhyaya, S. K. 2006, 'Computer Vision System for Automatic Control of Precision Furrow Irrigation System', American Society of Agricultural and Biological Engineers, 50(2), 371-8.

[12] Langat, P. K. and Raine, S. R. 2006, 'Using simulation modelling to improve the design and management of furrow irrigation in small-holder plots', Southern and Eastern African Rainwater Network, Mombasa, Kenya, <http://eprints.usq.edu.au/2143/>.

[13] Mailhol, J. C. and Gonzalez, J. M. 1993, 'Furrow Irrigation Model for Real-Time Applications on Cracking Soils', Journal of Irrigation and Drainage Engineering, 119(5), 768-83.

[14] McClymont, D. J. 2007, 'Development of a decision support system for furrow and border irrigation', PhD Thesis, http://eprints.usq.edu.au/4083/.

[15] McClymont, D. J., Smith, R. J. and Raine, S. R. 1999, 'An integrated numerical model for the design and management of furrow irrigation', International Conference on Multi-Objective Decision Support Systems, 1- 6 August, Brisbane, Australia.

[16] Montgomery, J. and Wigginton, D. 2008, 'Evaluating furrow irrigation performance: Results from the 2006-07 season', Surface Irrigation Cotton CRC Team Bulletin.

[17] Raine, S. R and Smith, R. J 2007, 'Simulation modelling for surface irrigation evaluation: Training in using SIRMOD and IPARM.' National Centre for Engineering in Agriculture, Publication 1000008/5.

[18] Raine, S. R, Purcell, J. & Schmidt, E. 2005, 'Improving whole farm and infield irrigation efficiencies using IRRIMATETM tools', Irrigation Association Australia, Townsville, Australia, <http://eprints.usq.edu.au/565/>.

[19] Raine, S. R and Shannon, E. L 1996, 'Improving the efficiency and profitability of furrow irrigation for sugarcane production.' In "Sugarcane: Research Towards Efficient and Sustainable Production p211-2 (Eds JR Wilson, DM Hogarth, JA Campbell and AL Garside), CSIRO Division of Tropical Crops and Pastures, Brisbane.

[20] Raine, S. R. and Walker, W. R. 1998, 'A decision support tool for the design, management and evaluation of surface irrigation systems', Proc. National Conference, Irrigation Association of Australia, 19-21 May, Brisbane. p117-23.

[21] Smith, R. J, Gillies, M. H, Shanahan, M., Campbell, B. and Williamson, B. 2009, 'Evaluating the performance of bay irrigation in the GMID', Irrigation and Drainage Conference, Swan Hill, Vic, Australia.

[22] Smith, R. J., Raine, S. R., & McCarthy, A.C. 2007, 'Managing spacial and temporal variability in irrigated agriculture through adaptive control', National Centre for Engineering in Agriculture (NCEA), Toowoomba.

[23] Smith, R. J, Raine, S. R and Minkovich, J. 2005, 'Irrigation application efficiency and deep drainage potential under surface irrigated cotton', Agricultural Water Management, vol. 71, no. 2, pp. 117-30.

[24] Smith, R. J. 1990, 'The distribution of water from rigid and lay-flat gated pipe', Proc Australian Society of Sugar Cane Technologists 1990 Conference, Townsville, p. 56-64.

[25] Strelkoff, T. S., Clemmens, A. J., Schmidt, B. V., 1998, 'SRFR Version 3.31—A model for simulating surface irrigation in borders, basins and furrows', US Department of Agriculture Agricultural Research Service, U.S. Water Conservation Laboratory, Phoenix, AZ.

[26] Strelkoff, T. S., Clemmens, A. J., Schmidt, B. V., Slosky, E. J., 1996, 'BORDER—A Design and Management Aid for Sloping Border Irrigation Systems', WCL Report 21, US Department of Agriculture Agricultural Research Service, U.S. Water Conservation Laboratory, Phoenix, AZ.

[27] Trout, T. J. 1990, 'Furrow inflow and infiltration variability impacts on irrigation management', American Society of Agricultural and Biological Engineers, vol. 33(4), 1171-1178.

[28] Turral, H. 1996, 'Sensor Placement for real-time control of automated border irrigation', Conference on Engineering in Agriculture and Food Processing, Paper No. SEAg 96/036.

[29] USDA-ALARC (US Department of Agriculture, Agricultural Research Service, Arid-Land Agricultural Research Centre) 2009, 'WinSRFR 3.1 Help & Manual - Surface Irrigation Analysis, Design & Simulation', 21881 N. Cardon Lane Maricopa, AZ 85238.

[30] Walker, W.R. 1997, 'SIRMOD II. Irrigation simulation software', Utah State University, Logan

[31] Walker, W. R. 1989 'Guidelines for designing and evaluating surface irrigation systems', FAO Irrigation Drainage Paper 45, viewed 15 June 2009, <http://www.fao.org/docrep/T0231E/T0231E00.htm>.

[32] Walker, W. R and Skogerboe, G. V. 1987, 'Surface irrigation theory and practice', Prentice-Hall, New York.