University of Southern Queensland
Faculty of Engineering & Surveying

Automated real time optimisation for control of furrow irrigation

A thesis submitted by

Richard Koech

in fulfilment of the requirements of

Doctor of Philosophy

Submitted: Septemeber, 2012

Abstract

Furrow irrigation is one of the oldest techniques of surface irrigation and is the most popular method for the irrigation of row crops. In Australia the method is widely used for the irrigation of cotton and in some years it has accounted for about 95% of the total production. The furrow system is however often associated with high labour requirement and low water used efficiency. In furrow irrigation the soil is used both as a medium for infiltration and also for conveyance of water from one end of field to the other. However, the spatial and temporal soil infiltration variability causes non-uniformity in water absorption rates and furrow stream advance rates. This significantly reduces water use efficiency because current design and management practices do not take this variability into account. Most operations in the furrow system are undertaken manually, and are hence labour-intensive.

Real time optimisation and control of furrow irrigation has been proposed for the management of infiltration variability. The system estimates the soil infiltration characteristics in real time and uses the data to control the same irrigation, potentially leading to improvement of water use efficiency. The major goal of this research was therefore to develop, prove and demonstrate an automated system for real time optimisation of furrow irrigation. The hypotheses of the research were that: (i) use of real time optimisation and control in furrow irrigation can lead to significant improvement in irrigation performance, and (ii) automation of furrow irrigation is feasible.

The system developed in this research is an integration of a simulation model and associated automation hardware and consists of five main components: (i) a water delivery system, (ii) an inflow measurement system, (ii) a water sensor to monitor advance of water along the furrow, (iv) computer running the simulation model (AutoFurrow), and (v) a radio telemetry system to facilitate communication among the system components. AutoFurrow uses a scaling technique to adjust the soil infiltration characteristic and determine the soil conditions prevailing for the particular irrigation. Hence it optimises the current irrigation to satisfy the soil moisture deficit and other user-defined objectives (for example target efficiency, uniformity and run-off) and determines the time to end the irrigation in sufficient time for effective control of the irrigation.

Trials to test and prove the new system were undertaken on two separate commercial cotton properties over two consecutive irrigation seasons. The system implemented for the field trials was not fully automated, and operations such as starting and cutting off flow was achieved manually. Apart from evaluations of the optimisation system, full advance data and other measurements were taken for all trials to enable a post-irrigation complete (actual) irrigation evaluation to be undertaken. Performances expected as per the grower's irrigation management practices were also evaluated. The SISCO simulation model was used for analysis of data.

The results suggested that the optimisation system was successful in delivering irrigation performance significantly better than achieved by the grower. However, in the 2010/11 irrigation season this performance (predicted by the optimisation system) was found to be slightly higher than the actual performance and much less than that suggested by a post irrigation optimisation undertaken using the full measured data for each irrigation. This suggested that the system had not reached its full potential and further improvements were necessary. Factors investigated for their possible contribution to performance of the real time optimisation system were: flow rate, objective function, selection of the model curve, and the infiltration scaling process. The investigations involved an exhaustive series of simulations using the SISCO model, varying each of these factors in turn.

The key changes in the evaluation methodology effected as a result of these investigations and used for the 2011/12 irrigation season trials were: the adoption of a simpler objective function consisting only of RE, and (ii) taking the average shape of the previous infiltrations curves and using it as the model curve. The benefit of these changes was clearly evident in the results obtained from the 2011/12 trials - the performance of the optimisation system improved and the difference between the actual performance predicted by the optimisation system was reduced to $\leq 4\%$.

This research has therefore achieved its overall goal of designing and testing a real time optimisation system for furrow irrigation. It has also successfully demonstrated the potential benefits of real time optimisation and shown that the automation of the furrow system is feasible. Further research has been recommended including a comprehensive economic analysis and the trialling of the system in bay irrigation.

Preface

The work presented in this dissertation on the development of an automated real time optimisation system for furrow irrigation is the original work of the author. This PhD research project was part of a larger project funded by the Cotton Catchment Communities CRC. The AutoFurrow software developed in the study was designed by the author; however, the source code (simulation engine) was provided by Dr. Malcolm Gillies while the coding was done by Bo Zhao. The telemetry system used for communication was assembled by Steve Rees.

The field trials, laboratory experiments and the subsequent analyses and writing of this entire dissertation were conducted by the author. The publications produced during the period of candidature are listed blow:

Koech, R. K., Smith, R. J. and Gillies, M. H. (2010), 'Furrow irrigation in the Australian cotton industry: alternative water delivery systems and their potential for automation', Technical Report, National Centre for Engineering in Agriculture, Toowoomba, Australia.

Koech, R. K., Smith, R. J. and Gillies, M. H. (2010), 'Hydraulic characteristics of large diameter gated flexible fluming', Irrigation Australia Conference and Exhibition 2010: One Water Many Futures, 8-10 June 2010, Sydney, Australia.

Koech, R. K., Smith, R. J. and Gillies, M. H. (2010), 'Automation and control in surface irrigation systems: current status and expected future trends', Southern Region Engineering Conference (SREC 2010), 11-12 November 2010, Toowoomba, Australia.

Koech, R. K., Gillies, M. H. and Smith, R. J. (2010), 'Simulation modelling in surface irrigation systems', Southern Region Engineering Conference (SREC 2010), 11-12 November 2010, Toowoomba, Australia.

Koech, R. K., Smith, R. J. and Gillies, M. H. (2011), 'Design of an automatic furrow irrigation system utilising adaptive real-time control', SEAg 2011 Conference, 29-30 September 2011, Surfers Paradise, Australia.

Koech, R. K., Smith, R. J. and Gillies, M. H. (2011), 'Trends in the surface irrigation systems in the Australian irrigated agriculture', SEAg 2011 Conference, 29-30 September 2011, Surfers Paradise, Australia.

Smith, R. J., Gillies, M. H. and Koech, R. K. (2012) 'Real time optimisation for smart automation of surface irrigation', U.S. Society for Irrigation and Drainage Professionals (USCID) Conference: Irrigated Agriculture Responds to Water Use Challenges - Strategies for Success, 3-6 April 2012, Texas, US.

Koech, R. K. Smith, R. J. and Gillies, M. H. (2012) 'Evaluating the performance of a real time optimisation and control system for furrow irrigation', Irrigation Australia Conference and Exhibition 2012: Droughts, Floods, Environment: Managing Consumptive Water Needs Sustainability, 26 - 29 June 2012, Adelaide, South Australia.

Certification of Dissertation

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged. I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated

Richard Koech
D1136791

Signature of Candidate | Date

ENDORSEMENT

Signature of Principal Supervisor | Date
(Prof. Rod Smith)

Signature of Associate Supervisor | Date
(Dr. Malcolm Gillies)

Acknowledgments

This research has come to fruition through the invaluable assistance I received from a great number of people over the last approximately three years. I would like to express my sincere gratitude to some of these people who were particularly instrumental to the success of my study.

Firstly I would like to sincerely thank Prof. Rod Smith and Dr. Malcolm Gillies, my principal supervisor and associate supervisor respectively, for their dedication and guidance throughout my study. I will forever cherish the knowledge you graciously passed over to me during our numerous Wednesday meetings and through written feedback on my work.

A big thank you to the entire staff and students of the University of Southern Queensland, who in one way or another, contributed to making my student life a memorable experience. I would like to covey my appreciation in particular to the staff in the Faculty of Engineering and Surveying (FOES) and the National Centre for Engineering in Agriculture (NCEA) for their excellent service and understanding. A big thank you to Dr. Jochen Eberhard, Steve Rees, Bo Zhao and Troy Symes (late) all from the NCEA and Justin Schultz of WaterBiz Pty Limited for their great assistance with the technical aspects of my research.

Thanks to the Cotton Catchment Communities CRC, FOES and NCEA; and by extension the Australian citizenry for generously funding and facilitating this research and my scholarship. I would also like to acknowledge and thank the following people for facilitating field trials in their properties: Nathan Bradley, Craig Saunders, Kim Bremner and Drew. The role played by staff of Agri-Science Queensland (especially Graham Harries) in identifying these field sites is much appreciated.

Special thanks to Carmel Hohn, Theresa Baldo, Noreen Pauli, Vincent Hall and their families for supporting my family to settle down in Toowoomba and to integrate into the local community. The moral support and company provided by the Kenyan, Sudanese and Congolese communities living in Toowoomba is greatly acknowledged. Special thanks to William Tong, Deng Mogok, Amira and Abuk for their incredible support over the years.

To my extended family, relatives and friends: thank you for your love, prayers and enormous moral support. Thank you all my siblings - Alice, Isaac, Esther, Priscilla, Sara, Daniel, David, Emily, Christopher, Florence and Viola for always being on my side. Special thanks to my treasured mum Grace Chumo and dad the late Mael Chumo for your sacrifices, love and protection. Thank you to my parents-in-law John Chepkwony, Esther Chepkwony and Grace Chepkwony, and all my brothers and sisters-in-law for their constant support.

Finally a very big thank to my dear wife Margaret for her love, moral support and company, both in good and turbulent times. Thank you for enduring and understanding my long absence in the course of my study. To our dear sons Abraham, Sydney and Ismael, thank you for being a source of motivation and inspiration.

RICHARD KOECH

University of Southern Queensland

Septemeber 2012

Contents

List of Figures

List of Tables

Notation

g	Acceleration due to gravity (9.81 m/s^2)
Δh	Operating head (m)
G	Upward movement of groundwater (mm)
y	Depth of flow (m)
x	Advance distance (m)
t	Time (minutes or seconds)
I_x	Infiltration rate at a distance x along the furrow (m^3/m/s)
I	Cumulative infiltration (m^3/m)
v	Velocity of flow (m/s)
S_o	Channel bottom slope
S_f	Channel friction slope
a, k and f_o	Modified Kostiakov infiltration parameters
τ	Infiltration opportunity time (min)
SW_2, SW_1	Final and initial depths of soil moisture stored respectively (mm)
I_d	Irrigation depth applied (mm)
P	Precipitation (mm)
R	Runoff expressed as a depth (mm)
D_d	Deep drainage (mm)

ET_a	Actual crop and soil evapotranspiration (mm)
D, Φ	Internal diameter of pipe or siphon (m)
L	Field or pipe/siphon length (m)
A, A_o,	Cross-sectional area of flow (m^2)
p_1, p_2	Pressure in the head ditch and the discharge point (N/m^2)
v_1, v_2	Velocity of flow in the head ditch and the discharge point(m/s)
Z_1, Z_2	Elevation of the PTB in the head ditch and the discharge point (m)
ρ	Density of water (1000 kg/m^3)
h_f	Head loss due to friction (m)
λ	Friction loss coefficient
α	Velocity head coefficient
Q, Q_o	Discharge or flow rate (l/s)
H_p	Pressure head (m)
F	Scaling factor
σ_y	Surface shape factor (dimensionless)taken to be constant (0.77)
σ_z	Sub-surface shape factor
p, r	Fitted parameters of the power curve advance function
I_s	Scaled infiltration (m^3/m)
C_{HW}	Hazen-Williams coefficient
β	Shape factor
a	Cross-sectional area of fluming when less than full round
m	Exponent on the discharge/velocity term in flow equation
n	Exponent on diameter or hydraulic radius term
V_v	Mean velocity of flow in equivalent circular pipe
d/w	Height-width ratio of layflat
C_d	Coefficient of discharge
N	Number of outlets from the closed end
F_N	Christiansen's F factor
L_s	Outlet spacing (m)
R	Pearson correlation coefficient

Acronyms & Abbreviations

ABS	Australian Bureau of Statistics
AE	Application efficiency (%)
AFI	Alternate furrow irrigation
AutoFurrow	Software developed for real time optimisation of furrow irrigation
CV	Coefficient of variation
DU	Distribution uniformity (%)
FAO	Food and Agriculture Organisation
FIDO	Furrow Irrigation Design Optimiser
GPIPE	Gated Pipe Simulation Program
Irrimate^{TM}	Suite of tools used for surface irrigation evaluation
NCEA	National Centre for Engineering in Agriculture
PST	Pressure sensitive transducer
PTB	Pipe(s) through the bank
RE	Requirement efficiency (%)
SISCO	Surface Irrigation Simulation Calibration and Optimisation
HGL	Hydraulic grade line
TCO	Time to cut off flow (min)
USQ	University of Southern Queensland
Eqn(s)	Equation(s)

Chapter 1

Introduction

1.1 Introduction

This dissertation is the culmination of approximately three years of research on the subject of automated real-time optimisation for control of furrow irrigation. This first chapter provides the essential background information to the topic and covers: (i) the science of irrigation and in particular furrow irrigation hydraulics, (ii) role and significance of irrigation in Australia, (iii) improvements in furrow irrigation, (iv) definitions of essential terminologies, and (v) impacts of the improvements in the surface systems. The chapter then sets out the research problem addressed in the dissertation, the specific objectives and the significance. An outline of the whole thesis is also provided.

1.2 Background

Irrigation simply refers to the artificial supply of water for plant growth. Irrigation is commonly used to grow crops and pasture in areas with insufficient rainfall. Irrigation is by far the largest consumer of fresh water. Out of the approximately

3800 km^3 of water used annually at a global scale, irrigation consumes about 70% with industry and domestic use accounting for 20% and 10% respectively (Molden 2007). Although irrigated land covers only approximately 20% of the world's cropped land, it accounts for about 40% of total food production (FAO 2003). The global demand for water is expected to increase with the increase in population, and agricultural water use will face increasing competition from industrial and domestic usage.

In the context of this dissertation, an irrigation system refers to the various components, devices and tools that are used for the supply and management of water in an irrigated field. This research focuses on the on-farm systems, implying that issues to deal with water sources and the conveyance of water to the farm will not be covered in detail. Irrigation systems or methods may be broadly classified as (i) sprinkler, (ii) drip or trickle, (iii) surface, and (iii) other minor systems such as use of buckets.

In sprinkler systems water is delivered using overhead sprinklers, which spray the water over the crop or land surface. Common configurations of sprinkler systems include: hand-move or portable sprinkler systems, solid-set system, travelling sprinkler irrigators (gun and boom), centre pivot machines and linear move machines. In the drip or trickle system water drips or trickles through small nozzles installed in pipes which can either be under or above-ground. The sprinkler and drip/trickle systems are also referred to as pressurised systems, as they operate under low pressure which often involves some form of pumping. These systems are however out of the scope of this dissertation and will not be discussed in any greater detail.

Surface irrigation refers to application methods in which water is conveyed over the field surface by gravitational force. In this case, the soil surface acts both as a means of conveying water from one end to the other and also the surface through which infiltration occurs. Surface irrigation is the main irrigation system both in Australia and in the world. In 2008-09 for instance, the system accounted for

46% of the total irrigated land, the majority of which is located in the Murray Darling Basin (ABS 2010). The system is particularly suited to the irrigation of broad-acre crops and those that need to be grown in a pool of water. Pasture for grazing and crops such as cotton and rice are mainly grown using surface systems. Surface systems in general are simple and have lower energy and initial capital requirements compared to the conventional pressurised systems.

The most common configurations of the surface system are basin, bay and furrow. A basin, as the name suggests is level in all directions, and is bounded by earthen embankments with a gate for water inlet. A basin can either be rectangular or square in shape. This system is popular for the irrigation of rice which is usually grown in ponded conditions. A bay (or border) consists of sloping, rectangular blocks of land with free draining conditions at the lower end. In Australia this method is the most popular for the irrigation of pasture. In furrow irrigation, one of the oldest techniques of surface irrigation, water is conveyed through small channels with a gentle slope towards the downstream end. The spacing of these channels or furrows generally correspond to the spacing of the crop to be established. Furrow irrigation is the most popular method for the irrigation of row crops in the world. The system is by far the most common method for the irrigation of cotton in Australia. In 2003-2004 for instance, this system was used on 95% of all the cotton farms (ABS 2008*a*). This dissertation focusses on real time optimisation and control of furrow irrigation; hence the system will be analysed in greater detail in the subsequent sections and chapters.

1.3 Basic surface irrigation hydraulics

The main factors that impact on the performance of furrow 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. The depth of application, furrow flow rate and time to cut off are management variables. For most irrigators, time to cut-off is the only quantity that can be varied to achieve a desired level of irrigation performance (Raine & Smith 2007).

As mentioned above, in surface systems the soil is used both as a medium for infiltration and also for conveyance of water from one end of the field to the other. However, the soil infiltration characteristics vary both with time and space (for example Smith et al. 2007, 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 differences in the initial soil moisture content. In furrow irrigation for instance, infiltration variability causes non-uniformity in water absorption rates and furrow stream advance rates (Trout 1990).

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 and runoff from the downstream end (Figure 1.1). Deep drainage losses are also prevalent in highly permeable soils under surface systems (Raine & Shannon 1996). Shorter applications times may reduce the risk of deep drainage and excessive run-off but may also lead to insufficient water at the downstream end (Figure 1.2). Infiltration variability in surface systems thus presents probably the biggest challenge to both designers and irrigators (Walker 1989) and significantly reduces irrigation water use efficiency (Trout 1990, Gillies 2008).

Real time optimisation and control of furrow irrigation has the potential to overcome the effects of the spatial and temporal infiltration variability. The potential improvement in irrigation performance using this approach has been demonstrated by Raine & Smith (2007) and Smith et al. (2005). The concept of real time optimisation and control is the cornerstone of this research, and therefore it

Figure 1.1: Application times too long

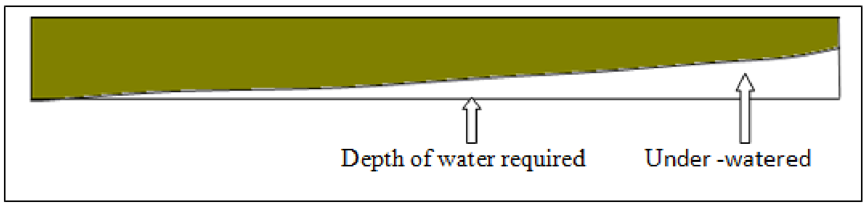


Figure 1.2: Application times too short

will be analysed throughout this dissertation.

Whilst there has been significant research aimed at minimising deep drainage losses in surface systems, evaporation losses in head ditches, furrows, bays and basins have largely been ignored. However, because of the relatively longer fields and irrigation application times typical of the Australian surface irrigated agriculture, these losses could be significant.

1.4 Irrigation performance

Water use efficiency or simply irrigation performance may be defined in many different ways (Dalton & Raine 1999), but it generally refers to the effectiveness of a water application system. Irrigation aims to supply the required amount of water to crops or pasture. The amount of water required to refill the soil moisture profile is termed as irrigation or water deficit. However, in some instances (for example when irrigation water is limited), less than the water deficit is applied thereby subjecting plants to a certain level of stress. This management practice is referred to as deficit irrigation.

The two most commonly used efficiency measures of an irrigation system are (i) application efficiency (AE) and (ii) requirement efficiency (RE). AE is probably the most commonly applied performance measure in surface irrigation and may be defined as:

$$\mathrm{AE} = \frac{\text{volume of water added to the root zone}}{\text{total volume of water applied}} \tag{1.1}$$

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

$$\mathrm{RE} = \frac{\text{volume added to the root zone}}{\text{water deficit prior to irrigation}} \tag{1.2}$$

Irrigation performance may also be characterised in terms of the uniformity or evenness of the applied water across the field. The uniformity measure commonly used in surface irrigation is distribution uniformity (DU) and may be defined as:

$$\mathrm{DU} = \frac{\text{average of the lowest 25\% of applied depths}}{\text{average applied depth in the whole field}} \tag{1.3}$$

Water use efficiency of typical surface irrigation systems under normal irrigator practices have been shown to be low and also variable. In an evaluation of cotton under surface irrigation in Queensland, Smith et al. (2005) obtained application efficiencies ranging from 17 to 100% and an average of 48%. The low efficiencies were attributed to excessive deep drainage losses. Raine & Shannon (1996) measured application efficiencies of 14 to 90% in furrow irrigated sugar in the Burdekin. And more recently in an evaluation of bay irrigation in the Goulburn Murray Irrigation District (GMID), Smith et al. (2009) obtained average application efficiencies of 72%.

1.5 Irrigation in Australia

Australia is one of the driest continents in the world and thus irrigation plays a significant role in the production of food and raw materials. Due to water scarcity however, only a small proportion of the agricultural land is irrigated. For instance in 2009-10, less than 1% of the approximately 399 million hectares of agricultural land was irrigated (ABS 2011). However irrigation accounts for approximately 30% food and non-food agricultural produce (Leonardi & Roth 2008).

Data from the Australian Bureau of Statistics (ABS) show that the total land area under irrigation in Australia has decreased by approximately 537 thousand hectares between 2002 and 2010 (Figure 1.3). The major reasons for this decline were (i) widespread drought; (ii) reductions of area under irrigation as a result of reduced water allocations; and (iii) agricultural establishments which sold out their water rights and reduced their acreages or stopped irrigation altogether (ABS 2008*b*, ABS 2010). Surface irrigation system has remained the main irrigation method in Australia, with the method used in 46% of the total irrigated land in 2008-09. However this represents a decrease of 28% in the acreage under surface irrigation experienced between 1990 and 2009. Figure 1.3 also shows that there has been an uptake in the use of the sprinkler and the drip/trickle irrigation methods in the same period of time.

1.6 Improving furrow irrigation

It has already been illustrated above that the furrow system is popular for the irrigation of broad-acre crops such as cotton. Some of the factors that make the furrow system attractive include: comparatively low initial capital requirement, use of generally unskilled labour and low energy and maintenance costs. Soil type also plays an important role in determining the suitability of the furrow system. For example, on heavy clay soils commonly used for growing cotton,

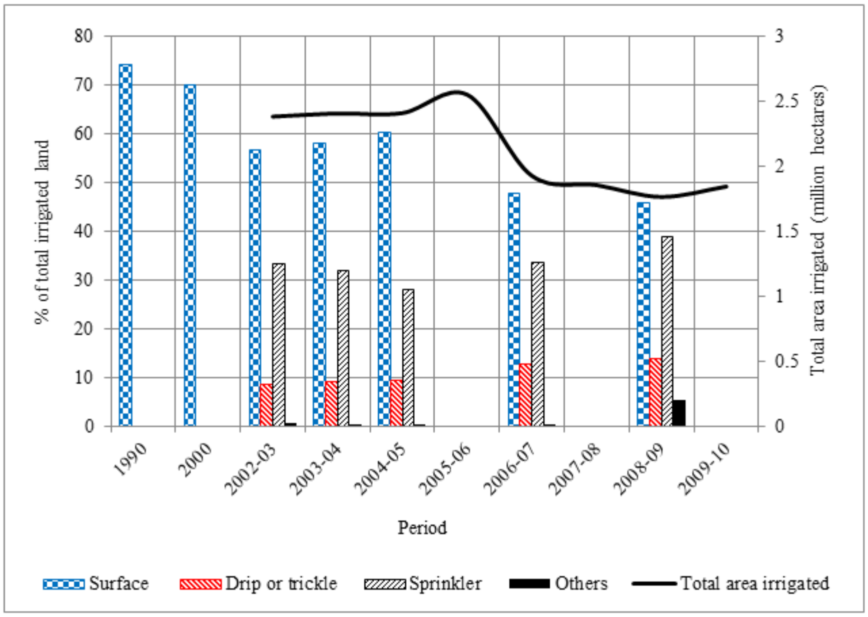


Figure 1.3: Area of land in Australia irrigated using different application systems [Plotted from data obtained from: ABS 2004, Graph 5.6; ABS 2005, Tables 2.1 and 4.2; ABS 2006, Tables 2.1 and 4.2; ABS 2008, Tables 2.1 and 4.2; ABS 2010, Tables 2.1 and 4.2; ABS 2011, Table 2.1]

furrow irrigation has traditionally been considered a suitable method. However the system is often associated with high labour requirement and low water use efficiency (Smith et al. 2005). Labour requirements under pressurised systems can be as low as 10% of the labour required in typical surface irrigation systems (Raine & Foley 2002). These are some of the reasons that have seen some previously furrow-irrigated fields converted into low pressure systems.

The conversion from surface to pressurised systems comes with a heavy initial capital investment. This investment cannot always be justified, as shown by a study of the dairy industry in the Lower Murray-Darling Basin (Doyle et al. 2009). This study concluded that adopting pressurised irrigation systems will not improve the viability of most irrigated dairy farms as the farmers need time to acquire a new set of skills. Wood & Martin (2000) also advised against the broad adoption of pressurised irrigation systems as the benefits were not automatic.

It would appear that the motivation behind the improvements that have been made to the furrow system in the recent past has been the need to reduce the labour requirement and to improve its water use efficiency. A lot of focus has gone to the latter especially because of the need to ensure sustainable use of water resources. The Federal and State governments in Australia have provided funding for improvements in the surface system on condition that the water saved is surrendered back to the environment (Plusquellec 2009). These improvements have come in the form of upgrades in the physical irrigation on-farm infrastructure and changes in the irrigation management practices, including automation and control. These will be covered in greater detail in the subsequent chapters.

1.7 Definitions

Automation and control engineering principles have traditionally been applied in industrial processes such as manufacturing and production. In the recent decades however, these principles have also been applied in precision agriculture including surface irrigation systems. Some of the more common terminologies that have hitherto been used in control systems engineering are defined below as they are used in most surface irrigation literature.

1.7.1 *Automation*

This is the process of performing operations without the need for constant human involvement except for periodic inspections and routine maintenance. A classic example of automation in surface systems is automatic opening and closing of border/bay inlets by use of actuators. In an automated irrigation system, management decisions such as time to cut off may be made automatically after a predetermined volume of water has been delivered (volume-based automation) or after pre-set times (time-based automation). The latter is more commonly applied in surface irrigation systems as it is simpler and less costly. Fully automated systems operate independently except for periodic checks and maintenance while semi-automatic systems usually have to be manually reset before the next irrigation event.

1.7.2 *Control*

This refers to management or regulation of irrigation in aspects such as size of inflow and time to cut off the inflow. Control can either be achieved manually or automatically. A control system can be defined as an interconnection of components forming a system configuration that will provide a desired response (Dorf and Bishop 2008) or simply a system that controls the operation of a process (Smith et al. 2007). Control systems may be classified as either open or closed-loop. In open loop systems, irrigation is initiated and controlled according to a pre-defined schedule. On the other hand, in the closed-loop systems control decisions are typically based on feedback from sensors. Most of the existing control strategies in irrigation are open-loop (Smith et al. 2007).

1.7.3 *Feedback control*

This refers to control decisions (for example time to cut off) made based on some form of measurement or feedback from the irrigation process. For instance water sensors may be placed anywhere along the furrow to provide feedback on the time of arrival of the water front. A common form of feedback control practised by irrigators is cutting off the flow of water when it has reached the end of the field. Irrigation evaluations by consultants is also a form of feedback control (Clemmens 1992). However in this case the feedback obtained is used to control future irrigations.

1.7.4 *Real-time control*

Real-time control as applied to surface irrigation implies that measurements taken during an irrigation event are processed and used for the modification and optimisation of the same irrigation event. Real-time control in surface systems is feasible when the control process is automated so that the feedback can be implemented rapidly. An example is when an irrigation event is monitored and the feedback is implemented while the irrigation is still underway. Some authors however have used the terms feedback and real time control interchangeably in surface irrigation systems (for example Clemmens 1992).

1.7.5 *Adaptive control*

This refers to the continuous variation of the control strategy in response to the changing parameters of the system. In surface irrigation for instance, infiltration or rate of water entry into the soil changes both temporally and spatially. A control system that takes cognisance of this variability is termed adaptive. The system may be termed as adaptive real-time control if the variation and control occurs in real time or rapidly.

1.7.6 *Optimisation*

Optimisation as it is referred to in surface irrigation is the process of manipulating the various design and management variables affecting the irrigation process with the aim of achieving the best or optimal outcome possible. This has traditionally been achieved through trial and error or irrigator experience, however owing to the advancement in computing technology in the recent past, the use of simulation models has been on the increase (McClymont 2007).

1.8 Impacts of improvements in the surface systems

1.8.1 Benefits

In automated surface irrigation systems, the irrigation process takes place in the absence of the irrigator (or operator). The excess labour as a result of automation can be re-deployed elsewhere in the farm or simply dispensed with. Labour is often required during night-time hours in irrigation operations, but this may be avoided with automation translating to comfort to both irrigators and operators. This partly explains why the benefits of automation have traditionally been seen as labour saving and lifestyle improvement, especially from the point of view of the irrigators.

The use of automatic structures and devices in irrigation guarantees timely farm operations (such as opening and closing of inlet bay structures) and eliminates (or at least reduces) the element of human error. This leads to water savings, the magnitude of which depends in part on the robustness of the control strategy in place.

That the water saving aspect of automation is somehow obscure is perhaps best illustrated by a survey undertaken by Maskey et al. (2001). When asked about their perceptions of the benefits of automation, the percentage of farmers who considered labour saving and reduction of water usage as having the greatest benefits were 59% and 19.3% respectively. The potential increase of land value as a result of automation was also widely recognised by the farmers.

Few researchers have attempted to quantify the benefits of automation in irrigation projects. Lavis et al. (2007) estimated water saving of 5 to 9% in the Shepparton Irrigation Region. Initial results from a bay irrigation project using an intelligent irrigation controller and wireless sensor network at Dookie, Northern Victoria, suggest that an average water saving of 38% can be realised (Dassanayake et al. 2001).

1.8.2 Level of adoption

There is limited published data on the proportion of irrigators who have adopted some form of irrigation automation in Australia. However it is clear that the majority of the automated systems are found in southern-eastern Australia (New South Wales, Victoria) and particularly within the dairy industry. Bay irrigation is the preferred method of irrigation in these areas. Statistics from Murray Valley Irrigation Area (Maskey et al. 2001) and Central Goulburn in Northern Victoria (Armstrong 2009) indicate that 8% and 11% of dairy farmers respectively were using some form of automation in their farming practices.

1.8.3 Barriers

Walker & Skogerboe (1987) cited lack of interest by potential manufacturers in investing in the design and manufacture of automation infrastructure because of perceived weak market. The low adoption of automation technologies was thus attributed to the scarcity and therefore expense of automation equipment. The survey of irrigators in the Murray Valley Irrigation Area (Maskey et al. 2001) rated automation equipment cost as the most important barrier to automation. The irrigators also added other priorities in the farm and the requirement of the farm re-design before automation as important barriers to automation. More manufacturers are expected to come onto the market as more irrigators adopt the new technology. This will inevitably lead to lower retail prices.

1.8.4 Future trends

The future will undoubtedly see more competition for the already scarce water resources. Governments and environmentalists will continue to advocate for a balance between the exploitation of water resources and sustainable environmental conservation. All water users, including irrigators, will be required to be more accountable in their use of the scarce resource. Farm labour will become scarce and expensive. It is widely anticipated that some of the farms presently under surface irrigation will eventually be converted to the various forms of low-pressure systems, but nonetheless surface irrigation will remain a dominant method for the foreseeable future (for example Gillies 2008, Raine 2006). It is likely that the current efforts to modernise and improve the water use efficiencies of the surface systems will intensify in the future.

Several factors work in favour of the surface systems, the initial capital requirement perhaps being the most significant. Most surface systems are gravity-fed from the water source with very limited pumping. The limited pumping involved means that the energy requirements (and therefore the carbon foot print) are also low. There is also the advantage of low maintenance costs involved and the use of generally unskilled labour.

As explained earlier in this chapter, conversion to pressurised systems is an expensive venture, and the benefits are not always forthcoming. Pressurised systems also rely heavily on energy, the price of which has been on a steady increase for several decades. The possibility of energy prices increasing to the point of rendering the pressurised systems unviable is not impossible.

It is highly likely that the research and improvement of surface systems will continue into the future. This will deliver performance similar to the pressurised systems at a lesser cost. But as with any new technology, automation and especially the use of telemetry, will take some time before irrigators can adopt in a broader scale.

1.9 Overview of research

1.9.1 Hypotheses

This PhD proposes that:

- Use of a real time optimisation system in furrow irrigation can lead to significant improvement in performance; and
- Automated real-time control of furrow irrigation is feasible.

1.9.2 Research problem

Adaptive real-time control has been proposed for the management of temporal infiltration variability (for example: Emilio et al. 1997, Mailhol & Gonzalez 1993, Khatri & Smith 2006, Turral 1996). This has the potential to improve the water use efficiency of the furrow system (as demonstrated by Smith et al. 2005, Raine et al. 1997). As already explained, none of the systems so far proposed have been widely accepted by irrigators.

One possible reason is that the benefits of such a system have not been clearly demonstrated to irrigators and researchers. Another factor is that most of the systems have tended to be expensive and complex. Hence the main goal of this research was to design a simple real time optimisation and control system for furrow irrigation and test in order to demonstrate its potential benefits.

1.9.3 Objectives

The aim of the project is to develop, prove and demonstrate an automated system for real-time optimisation and control of furrow irrigation for employment in adaptive real time control. The specific objectives are:

- evaluate alternative water delivery systems e.g. flexible fluming, bank-less channels, siphon and pipe through the bank (PTB);
- identify an appropriate numerical procedure to evaluate infiltration rates in real-time (while irrigation is underway);
- integrate modelling software with sensing, communication and control hardware; and
- prove the prototype system through appropriate field trials.

1.10 Significance of research

The expected outcomes and significance of the proposed project are as follows:

- Additional gains in water use efficiency through increased irrigation performance, improved uniformity of application along the length of the furrows and reduced runoff. Water logging and deep drainage losses are also expected to reduce;
- Potential increase in crop yield as a result of improved uniformity of application and reduced water-logging;
- Substantial labour savings as a result of automation;
- An improved understanding of how irrigation management must change in order to adapt to changes in field conditions; and
- Opportunity for many growers (especially cotton growers) who prefer to continue with the practice rather than convert to pressurised systems. The proposed system will deliver performance equivalent to the pressurised systems but at a much lower capital cost.

1.11 Structure of the dissertation

The outcome of about three years worth of research for this PhD has been presented in eight chapters. Briefly the contents of each chapter are as follows:

Chapter 1 - This first chapter provides an overview or 'big picture' of the entire body of work. Basic science of irrigation hydraulics and especially the infiltration process is provided. The role and significance of irrigation in Australia is discussed as well as the improvements that have been made to the furrow system and their impacts. Definitions of the terminologies commonly used in this dissertation are provided. The research problem and hypotheses are expressed, and also the objectives and the envisaged outcomes.

Chapter 2 - Previous work focussing on optimisation and control of furrow irrigation (and surface irrigation in general) is presented and evaluated in this chapter. In particular, existing and previous optimisation and control strategies are discussed and their limitations identified. The goal of this chapter is to identify the gaps that exist in the research area so as to be able to tackle the research problem appropriately.

Chapter 3 - This chapter presents the details of the optimisation and control system designed and developed for furrow irrigation, including the hardware and software components. The concept of real-time optimisation and control is explained, as well as the significance of infiltration variability. The system description and operation is provided, including the associated modelling and simulation.

Chapter 4 - The methodology used in the collection and evaluation of field data is detailed in this chapter. The evaluations of the optimisation system as well as complete evaluations based on actual measured data are described. The field trials were undertaken over two consecutive irrigation seasons. The location and a brief description of the field sites is provided in this chapter.

Chapter 5 - The results of the preliminary field trials (2010/11 irrigation season) are presented in this chapter. The results are presented as follows: (i) the model and scaled infiltration parameters, (ii) performance predicted by the optimisation system, (iii) performance based on actual (measured) infiltration, and (iv) performance achieved by the farmer. The challenges encountered in the field trials are explained.

Chapter 6 - The results of the series of evaluations of the preliminary results undertaken using the SISCO model are presented in this chapter. These simulations were undertaken to evaluate the effect of using alternative control and management strategies on the optimisation system performance. The parameters investigated are: objective function, flow rate, irrigation deficit, the infiltration scaling process, the model curve, advance distance and multi-furrow evaluation.

Chapter 7 - This chapter presents the final results undertaken during the 2011/12 irrigation season to prove the system. The changes effected in the these trials based on the experiences of the first trials are explained as well as their impacts.

Chapter 8 - The conclusions of the entire dissertation are presented in this chapter. Firstly, an overview of the entire dissertation is provided followed by the major conclusions arising from this research. Detailed conclusions based on the specific objectives and the key outcomes are presented. Finally, the key areas proposed for further research are identified.

Chapter 2

Review of automation, control and optimisation in surface irrigation

2.1 Introduction

The broad and specific context of this work has already been established in the previous chapter. In this chapter past work related to automation and control of surface irrigation is reviewed and evaluated, with emphasis on furrow irrigation. Although the focus of this dissertation is furrow irrigation, past work on border/bay and basin irrigation is included because some of the techniques used in those systems might possibly be adapted to the furrow system.

The various methods commonly used for on-farm water delivery in surface irrigation systems are reviewed and their suitability for use in automated systems assessed. Sensing and communication systems (including telemetry and SCADA systems), surface irrigation hydraulic modelling, existing simulations models and the techniques used for determining soil moisture deficit for irrigation scheduling are presented. Finally, the chapter presents a comprehensive review of past and existing designs of automated surface systems, including the model selected as the basis for the design of a furrow irrigation system for this project.

2.2 On-farm water delivery in surface irrigation systems

The mode of water delivery into a surface-irrigated field determines to a large extent the degree to which the irrigation system can be automated, controlled or optimised. Prior to reviewing other related aspects of surface irrigation, it is necessary to discuss the different methods of water delivery with particular emphasis on their potential for application in automated surface irrigation systems. Water delivery system as used in this dissertation refers to the technique employed to supply water to an irrigation basin, border or furrow. In the majority of the surface irrigation systems, either a head ditch running along one edge of the paddock or a buried pipe equipped with risers are used as sources of water. The common techniques used to transfer water from these sources are discussed below.

2.2.1 Gates

Gates are mostly metallic or reinforced concrete structures used to control the flow of water into an irrigation border or basin. These devices are also used in irrigation channels or head ditches to control the flow and level of water. Perhaps the most notable research to date on the automation of gates was undertaken by Humpherys (1995a, 1995b, 1995c). Gates with a single-function (either open to admit water or shut off the flow) are described in Humpherys (1995a) while dual-function gates (open and close) are detailed in Humpherys (1995b). The control of these devices may be achieved by a mechanical timer or electronic solenoid, that is, they are time-based open loop systems Humpherys (1995c). The two types of gates however require resetting prior to an irrigation event.

Table 2.1: Commercially available channel/outlet gates

Gate	Manufacturer	Features	Mode of control
SlipGate	Rubicon Systems Australia	Measure flow when fitted with sensors	Electromechanical actuators
FlumeGate^{TM}	Rubicon Systems Australia	Control and measure flow	Electromechanical actuators
Padman Stop	Padman Stops	Rubber set in concrete structure	Mechanical times
Water control gates (various)	AWMA Pty Ltd.	Actuation systems are custom made	Electromechanical, manual, hydraulic or pneumatic actuators

Adapted from:Agbodo et al. (1997)

Gates are widely used in the Australian irrigation industry. In the recent past there has been an increase in the number of manufacturers of irrigation equipment including gates in the country. Commercially available gates widely used in the Australian irrigation industry and their mode of activation are summarised in Table 2.1 (Agbodo et al. 1997). Apart from controlling the flow of water, a number of these gates can also measure the flow rate when fitted with sensors; thereby replacing Dethridge Wheels which have traditionally been used in the Australian irrigated agriculture (Smith & Nayar 2008).

2.2.2 Siphons

The use of overbank siphons is a feature of furrow irrigation in the cotton and grains industries in Australia. The siphons commonly in use range from 50 to 77 mm internal diameter while the lengths vary from 3.5 to 4.5 m. These siphons are mostly made of low density polyethylene. One or more siphons may be used per furrow, with the use of more than one siphon being most common where alternate furrow irrigation (AFI) is practiced.

For water to flow from the head ditch into the furrows, one end of the siphon must be submerged in the water in the head ditch, while the other end could either be free draining (Figure 2.1) or submerged in the furrow stream (Figure 2.2). In the first case the head driving the flow is taken as the difference between the water level in the head ditch and the outlet end of the siphon. In the latter case the head is taken as the difference between the water levels in the head ditch and the furrow stream.

Figure 2.1: Siphon operating with free flow

(source: Purcell 1994)

Figure 2.2: Siphon operating with submerged flow

(source: Purcell 1994)

The recommended equation for calculating the siphon discharge (Wigginton 2008) is that proposed by Bos (1989). The equation derived from the energy equation is expressed as:

$$Q = \frac{\pi D^2}{4} \left\{ \frac{2g\Delta h}{1.9 + \frac{\lambda L}{D}} \right\}^{0.5} \tag{2.1}$$

where Q is the discharge (m^3/s), D is the siphon internal diameter (m), g is the acceleration due to gravity (9.81 m/s^2), Δh is the operating head (m), λ is the friction loss coefficient, and L is the siphon length (m). The value 1.9 in the denominator reflects the minor loss between the head ditch and the furrow.

In Eqn. 2.1 above the siphon diameter term is squared while all the factors influencing the siphon discharge are raised to power 0.5. The implication here is that siphon internal diameter is the single most important factor affecting the siphon discharge. For instance, a 10% increase in diameter of a 50 mm diameter, 4 m long siphon operating under a head of 500 mm leads to a 23.6% increase in discharge. On the other hand, a corresponding 10% increase in operating head results in only a 5% increase in discharge. Where the available operating head in the head ditch is limiting, irrigators have the option of using more than one siphon or siphons of larger diameter in order to increase furrow inflows. Both of these options will obviously decrease the number of furrows that can be irrigated at a time.

Published data suggest that there can be significant furrow-to-furrow inflow variability in the siphon application method. Trout & Mackey (1988) measured a coefficient of variation (CV) of 15% with a range of 7 to 24% in siphon tubes supplying 60 consecutive furrows. Carter & Grabham (2008) reported variations ranging from 27 to 152% of the mean siphon flow.

Spatial variability in siphon discharge at the field scale may be caused by:

- level and slope in the head ditch which affects head available on the siphons;
- differences in lengths, cross-sectional area and roughness of the siphons; and
- differences in the orientation and level of points of discharge of the siphons.

Fluctuation in the level of water in the head ditch is an important cause of siphon discharge variation with time.

The uniformity of furrow inflows is a major determinant of irrigation performance at the field scale (Smith & Gillies 2010). The accuracy of an evaluation based on a single furrow will therefore be affected as a result of siphon discharge variability. It is however possible to design head ditches using hydraulic models in order to minimise variability in outflows (Smith & Gillies 2010)

Perhaps the main drawback of siphons in the irrigation industry is that they have to be started or primed manually. This involves dipping one end of the siphon into the water in the head ditch and drawing the water in by way of creating suction. Other problems associated with the use of siphons include blockage by trash in the head ditch and drastic reduction of water level in the head ditch which may lead to cessation of discharge.

An interesting fairly recent development is the use of a motorised priming unit to start up large overbank siphons (SPACEPAC 2010). However this technique is not feasible for control of individual furrow siphons. On the other hand, the National Centre for Engineering in Agriculture (NCEA) based at the University of Southern Queensland has developed a siphon flow meter and flume flow meter for measuring discharge through a siphon and runoff from the field respectively. These flow meters are commercially available as part of Irrimate^{TM} suite of tools commonly used in the evaluations of surface irrigation systems (Dalton et al. 2001).

The increased labour cost especially in the developed countries has made the need to automate furrow irrigation more relevant. Automation of siphon discharge is technically difficult. Siphons operate independently from each other and tens or hundreds of siphons may be in use at any one time. It would probably be infeasible to automate each one of these siphons. The other challenge facing the automation of siphons is the fact that head ditches are typically kept empty and are only filled with water just before an irrigation event.

2.2.3 Pipes-through-the-bank (PTB)

PTB, made of materials such as PVC and polyethylene, are used to draw a large quantity of water from the head ditch into a group of irrigation furrows or border/basin. In the cotton industry for instance pipes of about 300 mm internal diameter are used to deliver water to between 12 - 20 furrows. To constrain the water to flow only into the intended furrows, rotorbucks or earthen embankments are constructed in the space between the PTB outlet and the cropped area.

Hydraulically, PTB are similar to syphons and may be designed using the same methods. The discharge through the PTB is a function of the pipe characteristics (internal diameter, length and roughness) and the head of water above the inlet in the head ditch. For most irrigators, the available head in the supply ditch influences the size of PTB used and hence the number of furrows that can be irrigated by a single PTB. Obviously cost is also an important consideration in sizing PTB.

There is limited published data on the performance of PTB-fed furrow irrigation systems. In a preliminary investigation on siphon-less irrigation systems, (Hood & Carrigan 2006), found no significant difference between the irrigation performance of the PTB and the conventional siphon-irrigated furrows. It is however expected that the larger the number of furrows served by one PTB, the harder it is to attain uniform flow into each furrow. Carter & Grabham (2008) point to the possibility of accelerated flows in some furrows especially those that are wheel-tracked or slightly lower in elevation. Maintenance of the rotorbucks is often required throughout the irrigation season.

The majority of the PTB in use in the cotton industry have a flap valve and an extended arm at the inlet point in the head ditch side of the bank used to control flow (Figure 2.3a). The opening and closing is often done manually, but there is a great potential for automation using existing technologies. This was demonstrated at a furrow irrigation automation trial site at in the Gwydir Valley (Figure 2.3b) whereby each PTB inlet mechanism was automated allowing remote control using the 'Aquator' system (AWMA 2009).

(a) Manually operated PTB **(b) Automated PTB**

Figure 2.3: PTB in the cotton industry

The use of PTB may lead to significant labour savings even when they are operated manually. Hood & Carrigan (2006) estimated a labour saving of 60% when compared to siphons. When automated and remotely controlled as in Figure 2.3b, labour requirement will be limited to periodic inspection.

2.2.4 Gated pipe

Gated pipes used for distributing water into irrigation furrows can either be rigid (made of plastic or aluminium) or flexible/layflat with outlets to each furrow. The outlets, which can either be fixed or adjustable, are normally spaced according to the crop row spacing. Rigid gated pipes are rarely used in the Australian irrigation sector mainly because of difficulty experienced in transportation. Layflat is widely used in the sugar industry, but has so far not been successfully applied in the cotton industry because of the high flow rates required (Smith & Gillies 2010).

The hydraulic performance of gated pipe is primarily a function of the gate characteristic and pipe diameter. In the case of gated layflat, hydraulic characteristics are also influenced by the shape of the layflat which in turn varies with the fluid pressure (Humpherys & Lauritzen 1962). To determine the frictional losses, the Darcy-Weisbach, Hazen Williams and Manning equations may be used (Humpherys & Lauritzen 1964). However these methods must be modified to factor in the shape factors of the layflat. Humpherys & Lauritzen (1964) suggested the experimental calibration of the friction coefficient in the Darcy-Weisbach equation. Further work by the same author produced a plot of head-diameter and height-width ratios which can be used to determine the cross-sectional area of the layflat at any degree of roundness.

The fluid velocity and therefore the frictional losses in a gated pipe reduce along the length of the pipe. The 'F' factor method, developed by Christiansen (1942) has been used to estimate frictional losses in gated pipes. However the assumptions inherent in this method may lead to unacceptable errors in the determination of the gate outflows (Smith 1990, Scaloppi 1988). Smith et al. (1986) based on earlier work by McNown (1954) formulated a theoretical model suitable for the hydraulic design of gated pipe which culminated in the computer program GPIPE. The program was originally designed for rigid gated pipe and has not been fully calibrated for use in flexible pipe.

Trout & Mackey (1988) reported a coefficient of variation (CV) of 25% in furrow inflows from a gated pipe (rigid) delivery system. This variability is a matter of the hydraulic design of the gated pipe system. Computer simulation programs for instance GPIPE (Smith 1990) can be used to reduce this variability. A detailed discussion of the hydraulic characteristics of the layflat gated pipe is found in Appendix A.

2.2.5 Bankless channels

As the name suggests, bankless channel systems are a series of bays whose supply channel or head ditch has no bank in the field side. The bays may be level or with a small slope in either direction (that is, towards or away from the channel). These systems are relatively new to Australia. Published literature suggests that they were initially used in the 1990's to improve the water use efficiency of rice based farming systems (Grabham et al. 2008).

A common configuration of bankless channel irrigation is shown in Figure 2.4. The upward slope towards the tail-end of the bay ranges from 0.01 to 0.08% while the elevation difference between the bays is about 0.15 m (Grabham et al. 2009). The bankless bays are irrigated in sequence, starting with the one nearest the supply inlet. Gates are installed along the bankless channel aligned with each bank separating the bays and are used to block water forcing it to flow along the furrows of a single bay. Once the bay has been irrigated, the gate is opened thus water from the supply channel as well as the drainage from the previous bay is admitted into the next bay.

A novel evaluation method suitable for bankless channel irrigation systems is described in Grabham et al. (2009). This evaluation suggested that the performance of bankless systems is poor, with considerable variability in the discharge to each bay, the depth applied to each bay, and also in the furrow discharges within each bay.

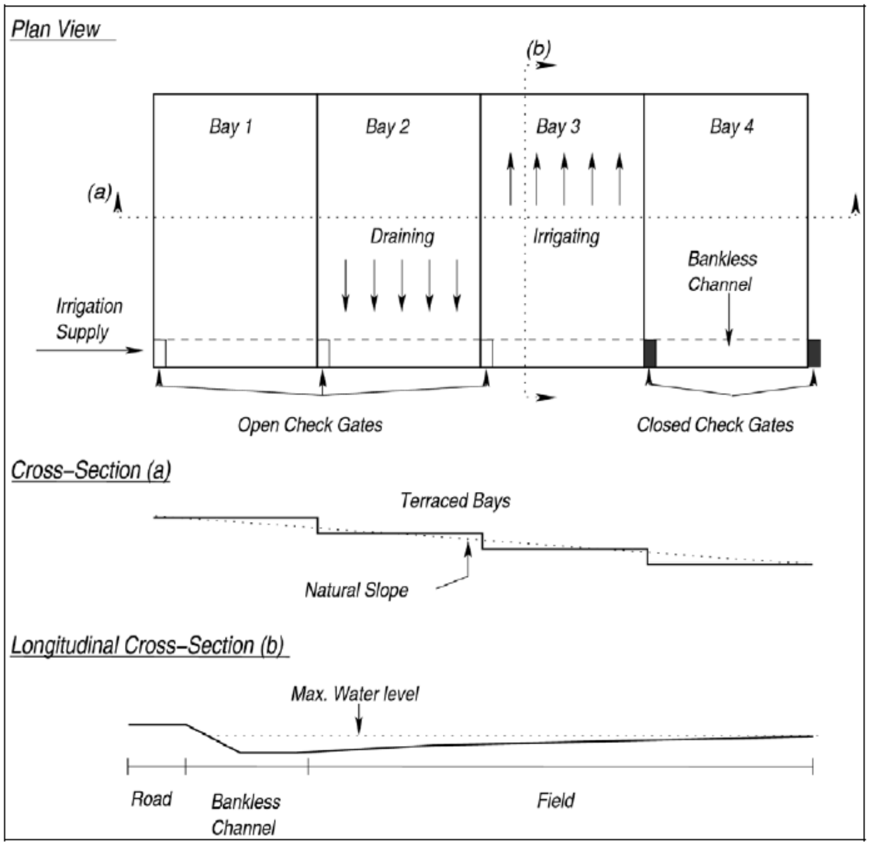


Figure 2.4: Schematic diagram of a bankless channel irrigation system

(source: Grabham et al. 2009)

Bankless channels offer significant potential for labour savings since water flows automatically along the furrows when backed up by the closed gate. Also, there is a possibility of automating the check gates by using the techniques that have successfully been applied in the conventional bay irrigation. As runoff from one bay is utilised in the subsequent bay, the cost associated with recirculating the tail water is eliminated. A bankless-irrigated field in St George is shown in Figure 2.5.

Figure 2.5: Bankless channel irrigated field in St George, Queensland

2.3 Sensing and communication systems

2.3.1 Advance measurement

Irrigators often use their intuition and experiences to determine the time to cut-off water flow into an irrigation bay/basin or furrow. In bay irrigation for instance, the inflow is commonly cut-off when the water front reaches two thirds of the distance down the bay (Dassanayake et al. 2001).

Sensors that are now routinely used in surface irrigation in Australia include Irrimate^{TM} water sensors, Padman radio bay sensors and Padman pneumatic bay sensors. Irrimate^{TM} advance sensors, commonly used in the evaluation of furrow irrigation, are placed at various points along the length of the field and are triggered by the advancing water front. The advance times are downloaded to a hand-held computer after the irrigation event. Padman radio bay sensors are placed at predetermined points along the irrigation bay. They are triggered by the advancing water and a signal is sent via radio links to the bay gate to cut-off the inflow. Pneumatic bay sensors are connected to the automatic gates by air-filled pipes. When the advancing water enters the sensor the air inside the pipe is pressurised thereby activating the opening and closing of the automatic gates (Armstrong 2009).

The use of a remote sensing vision system consisting of a camera placed at the downstream end of the field to monitor the advance of water along the furrows has been trialled by McCarthy (2004) and Lam et al. (2007). No sensors are placed in the furrows; hence the technique is less laborious and does not impede the use of machinery. Field tests conducted by the latter demonstrated that the vision system was able to determine the leading edge of water with an average error of 1.2 m. Discoloured water and overcast skies were found to affect the accuracy of prediction. These tests were carried out in very short furrows (140 m) while the position of the leading edge of water was monitored at a distance of 76.2 m from the end of the furrow. There is no evidence that the system has been tried on long furrows (sometimes >1000 m) typical of the Australian irrigated agriculture. The system tested by McCarthy (2004) concluded that terrestially based vision systems are infeasible for long furrows.

2.3.2 Telemetry and SCADA systems

Telemetry basically means assessing and/or transmitting data, and controlling a system remotely. The use of telemetry systems in surface irrigation systems is a fairly recent development. These systems are vital components of automatic surface irrigation methods for they allow measurement of various parameters (for example inflow, advance and soil moisture) from a remote location and the results are conveyed to a central location mainly via some form of radio communication.

Telemetry systems have been integrated with SCADA (Supervisory Control and Data Acquisition) systems in automated surface irrigation systems in Australia (Smith & Nayar 2008, Armstrong 2009). The AWMA Aquator system (mainly used to control bay/basin outlets), and RUBICON's FarmConnect^{TM} (used for water metering, irrigation scheduling and on-farm automation), both use SCADA platforms and allow remote control of these devices.

2.4 Hydraulic modelling

Hydraulic modelling (or simulation modelling) 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. The models permit evaluation of components of the water balance that cannot be practically measured such as the distribution of applied depths. The application of hydraulic modelling in surface systems, the governing equations and a review of existing models is presented below.

2.4.1 Governing equations

In surface irrigation, water infiltrates into the soil profile as it flows along the surface. Due to the nature of the soil infiltration characteristic (Walker 1989), the flow is both spatially varied and unsteady (Walker & 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. 2.2) and motion or momentum (Eqn. 2.3).

$$\frac{\delta Q}{\delta x} + \frac{\delta A}{\delta t} + I_x = 0 \tag{2.2}$$

$$\frac{v}{g}\frac{\delta v}{\delta x} + \frac{v}{gA}\frac{\delta Q}{\delta x} + \frac{v}{gA}\frac{\delta A}{\delta t} + \frac{I}{g}\frac{\delta v}{\delta t} + \frac{\delta y}{\delta x} = S_o - S_f \tag{2.3}$$

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. 2.2) as it is the dominant of the two equations (Raine & Smith 2007) and is the simplest approximation of the Saint Venant equations (McClymont 2007).

2.4.2 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 combined with a more rapid recession. The infiltration characteristic of the soil is therefore a key variable that determines the performance of a surface irrigation application system (Raine & Smith 2007). The most commonly used model to describe the soil infiltration characteristic for surface irrigation is the Kostiakov-Lewis equation:

$$I = k\tau^a + f_o\tau \tag{2.4}$$

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.

2.5 Existing simulation 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 two models and the recent Australian models are described below.

2.5.1 SIRMOD

SIRMOD (surface irrigation simulation, evaluation and design) developed by Utah State University is a comprehensive simulation software package for simulating surface irrigation hydraulics. 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. SIRMOD version II is commercially available through Irrimate^{TM} (a suite of hardware and software tools developed by the NCEA).

SIRMOD is used both as a field evaluation tool and to evaluate alternative field designs and management practices. As a design tool, SIRMOD is used to predict the irrigation performance under alternative field parameters (length and slope). This may be useful in the development of new irrigation farms or the modification of the existing ones. SIRMOD can also be used to identify performance improvements under different management practices. For example it can be used to determine the flow rates and cut-off times that give the best irrigation performance.

SIRMOD requires the following data in order to run a simulation (i) field characteristics (field/furrow geometry and infiltration functions); and (ii) model parameters (simulated inflow and time to cut off). Commonly as an improvement over the two point approach the infiltration functions are estimated outside SIRMOD using volume balance models such as IPARM (Gillies & Smith 2005, Figure 2.6). The SIRMOD main output screen (Figure 2.7) includes a plot of the distribution of infiltrated water, simulated irrigation performance, volume balance and the runoff hydrograph.

Traditionally, SIRMOD evaluations undertaken earlier in the season are used to modify and improve future irrigations. The potential for the model to be used as a ‘quasi real time management tool’ was investigated by Hornbuckle et al. (2005). This trial was undertaken in a farm irrigated using siphons in consecutive

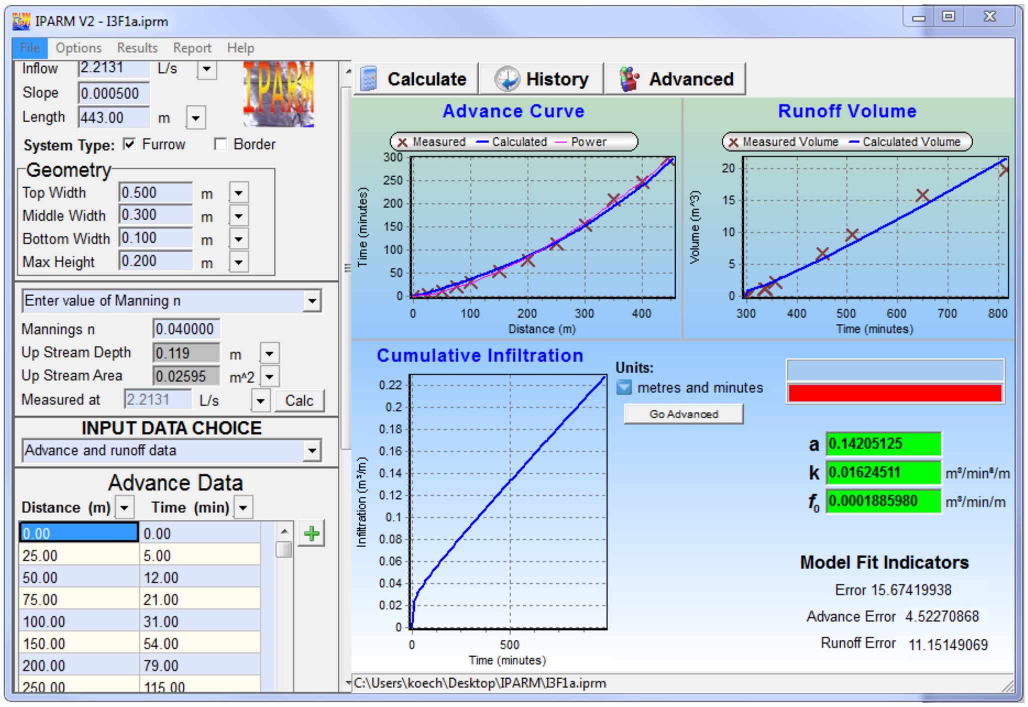


Figure 2.6: IPARM main user interface

sets. It involved using the optimised parameters obtained from the previous set to optimise the irrigation performance of the subsequent irrigation set. This approach resulted in water savings of approximately 0.6 ML/ha and a decrease in runoff volumes of about 0.15 ML/ha. However the assumption taken in the study that the soil infiltration characteristics are uniform across sets for a given farm may not be applicable in all cases.

In Australia, SIRMOD has been widely accepted as the standard for the evaluation and optimisation of furrow irrigation and can also be used to simulate basin and border irrigation (Gillies 2008). However, the model is often seen as data-intensive. Optimisation is conducted manually by trial and error method. Also, the model was designed for use by skilled persons (mainly researchers and irrigation consultants).

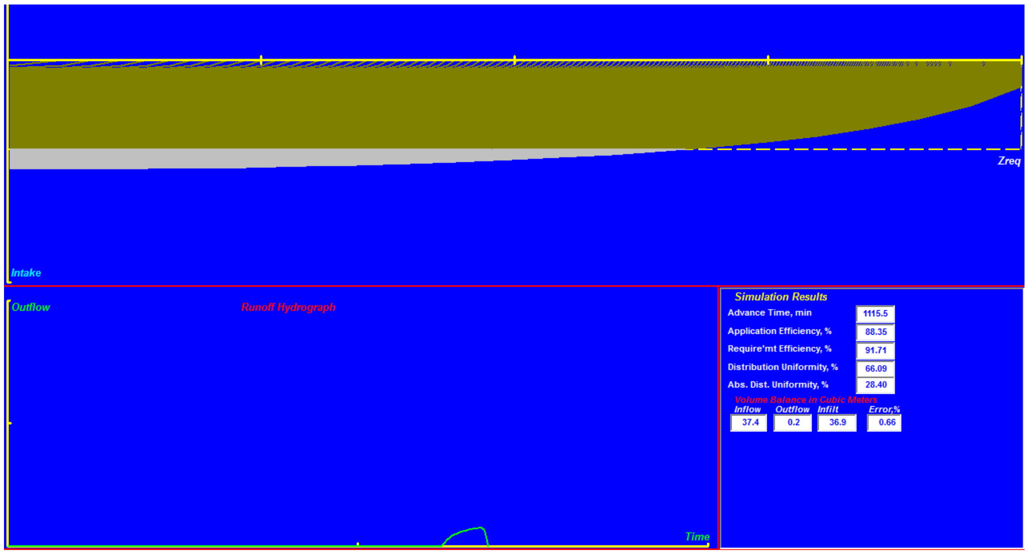


Figure 2.7: SIRMOD main output screen

2.5.2 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 (that is, 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 (Figure 2.8).

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

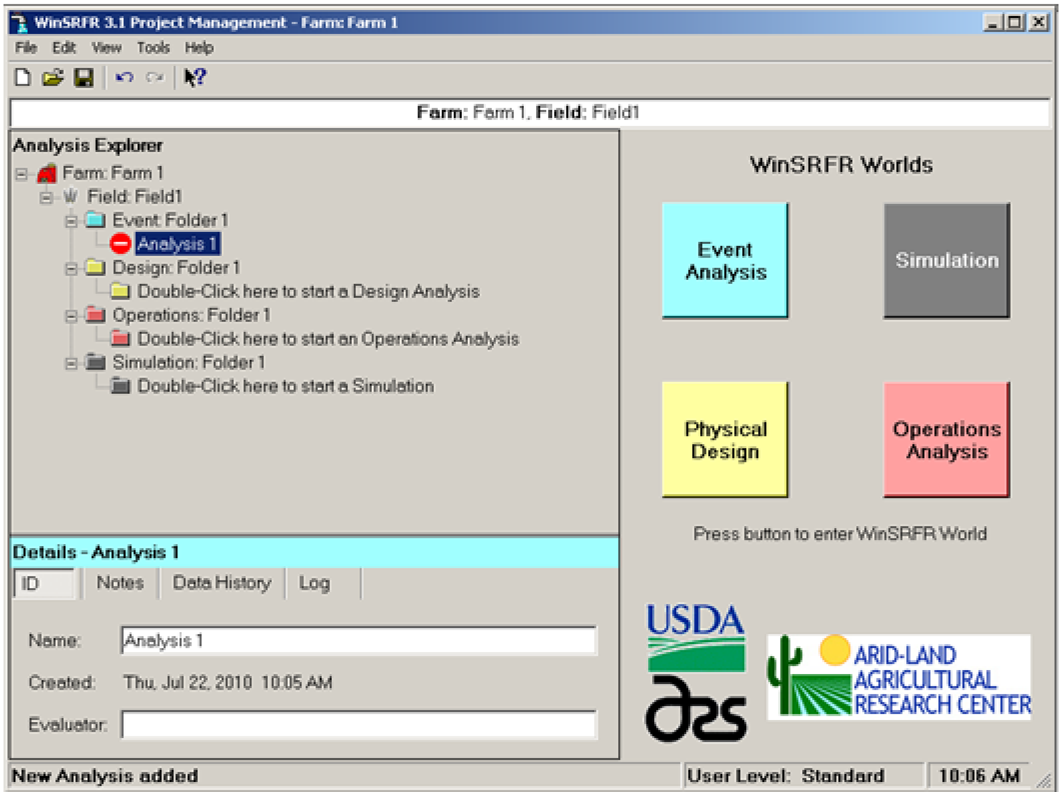


Figure 2.8: WinSRFR 3.1 Project Management window

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/download.htm?softwareid=250*). The software is used by researchers and farmers in the US, but there is little indication of its application in the Australian irrigation industry. Similarly there is no evidence that the model has been used for real time control of surface irrigation. The model has not been pursued further in this dissertation.

2.5.3 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. 2008a) 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 (the characteristics of SISCO are described in subsection 2.5.4 below).

An interesting attempt to find an analytic solution to the kinematic wave approximation resulted in the development of the AIM model (Austin & Prendergast 1997). Developed specifically for bay irrigation of cracking clay soils, AIM is simple to use but under certain conditions suffers from unacceptable inaccuracy.

2.5.4 The SISCO model

The SISCO model (Figure 2.9) is similar in many aspects to the pioneer SIRMOD model (Walker 1997), and requires standard parameters such as the field details, inflow data (either constant or variable), furrow geometry, infiltration parameters and irrigation deficit. It is also based on the complete hydrodynamic model and therefore potentially more accurate than WinSRFR which uses simplified forms of the momentum equation.

The distinct difference between the SISCO model and the SIRMOD model is that the former is self-calibrating. The calibration process involving the estimation of the three Modified Kostiakov infiltration parameters and Manning roughness can be undertaken using either one or a combination of the following variables: advance data, runoff, recession and water depth in the furrow. Simulation of the irrigation can also be performed on a single or multi-furrow basis.

One other important feature of SISCO over alternative models is the optimisation tool. This tool simulates all possible combinations of up to two management variables (e.g. inflow rate and cut off time) and assists the user in identifying the optimal combination of these variables in order to satisfy the performance criteria specified by the irrigator. SISCO is a robust model and presents a suitable platform for the development of real-time optimisation simulation models.

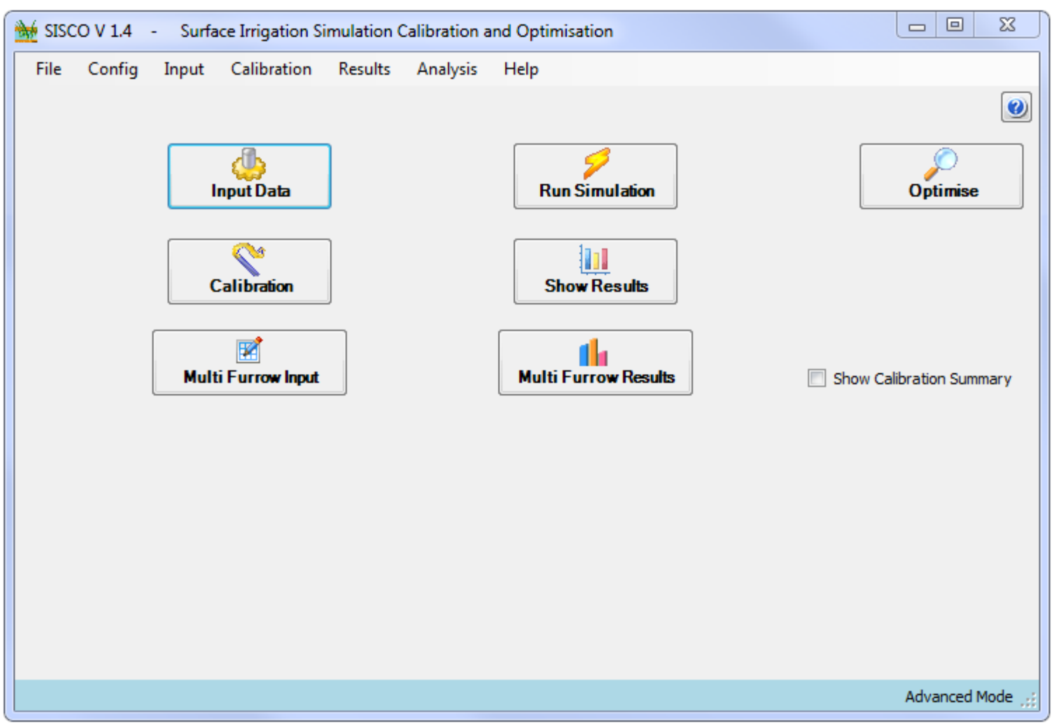


Figure 2.9: SISCO main screen

2.6 Soil moisture deficit

Soil moisture is said to be at field capacity after excess water from rainfall or irrigation event has drained off. Due to evapotranspiration (crop water use and evaporative losses), soil moisture may gradually drop to a point where plants start to experience water stress (wilting point). Soil moisture deficit is the amount of water required to bring the moisture content back to field capacity. Irrigation is an artificial way of refilling the soil moisture profile after the soil moisture content depletes to a nominated point.

Reliable estimation of the soil moisture deficit is a prerequisite to effective irrigation scheduling, and also has a major impact on the evaluation of surface irrigation (Raine & Smith 2007). An underestimation of the irrigation deficit reduces the simulated application efficiency and increases the requirement efficiency, and vice-versa. Since irrigation deficit has an effect on the simulated irrigation performance, it therefore follows it may potentially have an effect on optimised furrow systems.

Gravimetric and neutron scattering methods are used for direct measurements of soil water status. Though both methods are fairly accurate, the procedures are time-consuming and expensive. Capacitance probes such as the EnviroScan system have gained wide acceptance by commercial farmers and researchers in Australia because of their ability to continuously monitor the soil water content and the ease with which the information can be accessed.

The use of the soil moisture balance method (or water budget) to determine soil moisture deficit requires the measurements or estimation of factors such as precipitation, evapotranspiration, irrigation and drainage (Eqn. 2.5). In this method, the initial soil moisture content must be determined. This approach is less accurate and periodic checks using direct measurements are desirable (ASABE 2008).

$$SW_2 = SW_1 + I_d + P - R - D_d + G - ET_a \tag{2.5}$$

where SW_2 and SW_1 are the final and initial depths of soil moisture stored respectively (mm); I_d is the irrigation depth applied during the time period (mm); P is the precipitation (mm); R is the runoff expressed as a depth (mm); D_d is the deep drainage (mm); G is the upward movement of groundwater (mm); and ET_a (mm) is the actual crop and soil evapotranspiration (Allen et al. 1998).

Soil water content can also be inferred from the measurements of soil water potential. The Tensiometer is probably the most common equipment used for this purpose. However, measurements obtained from all these techniques cannot represent real time soil moisture content across the entire field because of soil spatial variability (Emilio et al. 1997).

In surface systems employing real-time optimisation and control, timely prediction of the soil moisture status is of essence. A number of approaches have been proposed for obtaining soil moisture status in real time. An automated method of collection of soil data (from sensors installed in the soil profile) designed by (Fisher 2007) uses a low-cost microcontroller circuit. The method allows for continuous logging of soil moisture status and requires minimum labour.

In Australia a relatively new technique for obtaining soil moisture status has been proposed by Hornbuckle et al. (2009). The procedure uses a combination of satellite images and ground weather station to determine the crop water use and hence the irrigation requirement from the water balance method (Eqn. 2.5). The service is available through the internet, and registered irrigators are able to receive real time soil moisture status of their paddocks via a text message sent to their mobile phones. This approach has been named 'IrriSatSMS' because it utilises satellite imagery and text messaging (SMS).

2.7 Automated surface irrigation

2.7.1 Introduction

The introductory chapter of this dissertation has argued that the motivation behind the developments that have been made to the furrow system (and surface irrigation in general) in the past has been the need to reduce the labour requirement and improve the water use efficiency of the system. It would appear that labour saving was the major driving force for the initial developments in these systems; hence the automation of the water delivery system, and later the use of wireless telemetry for communication among various system components (subsection 2.3.2). Most of these earlier designs had only one aspect automated (mostly the water delivery mechanism), and hence the systems were generally termed 'semi-automated.'

In addition to labour reduction, the motivation towards the current advancements in surface systems seems to be the desire to optimise the dollar output of the scarce water resources while at the same time conserving the environment. This has largely involved the integration of automation hardware with intelligent computer and electronic systems for a more efficient management of water resources. This has enabled measurements such as inflow and estimation of soil infiltration characteristics to be taken in real time. Irrigation performance optimisation strategies that have been used include infiltrated depth, minimisation of runoff and maximisation of application efficiency. Regulation of the irrigation application time and reduction of inflow (cutback flow regime) are the common control methods that have been used to achieve the desired irrigation performance. This approach has been referred to as 'smart automation' because of the use of intelligent and adaptive systems.

Smart automation of surface irrigation systems and other reforms in the irrigation industry have been supported and financed by the Federal and State governments in Australia (Plusquellec 2009). The anticipated benefits of these initiatives are increased profitability of irrigation enterprises and environmentally sustainable use of the scarce water resources.

It is clear from published work that the bulk of the developments that have occurred in surface systems especially as regards to automation and control have been biased towards bay and basin application systems. These systems are generally suited to automation because of more even distribution of water over the soil surface, while developments in the furrow system have been stifled by the challenge and potential cost of ensuring uniform distribution of water into individual furrows (Humpherys 1971). The past design methods in both the furrow and bay/basin systems are discussed below.

The definitions of the more common terminologies adapted from control engineering and now used in irrigation literature were provided in Chapter 1. For the purpose of a review of automated surface irrigation systems, past design approaches in both furrow and bay/basin systems have been categorised as follows:

- Automated systems - focussed only on the use of automatic hardware, both semi and fully automated. This is commonly referred to as 'dumb automation'.
- Feedback control systems - involving some form of measurement but control is purely by distance or time to cut off.
- Automatic real time optimisation and control systems - systems referred to as 'smart automation' above.

2.7.2 Automated systems

The single and double function gates mentioned in subsection 2.2.1 were used in the semi-automation of border and basin irrigation systems. They were installed in the supply ditch to control the flow of water into the border/basin. With the use of single-function gates in the border system, which previously used check gates along the head ditch (Humpherys 1995a), a reduction in irrigation time of 50% was achieved. The dual function gates (also used in the border system) achieved even a higher reduction in irrigation time of 64% compared to siphon application method (Humpherys 1995b). The above reduction in irrigation time was achieved while the system was operated manually; the control system installed later used mechanical timers or electronic solenoids (Humpherys 1995c). Apart from reduction in irrigation time achieved from these two research projects, increased water use efficiency, decreased labour requirement and irrigator convenience were cited by the author as benefits of the improved system.

Surge flow irrigation is achieved by intermittent application of water to furrows, as opposed to the conventional continuous flow. Two commercially available surge flow irrigation systems were described by Walker (1989). The 'dual line' system commonly used by irrigators who already had gated pipe system in place, used an automated surge flow valve to switch the flow between the two sides of the pipe system. In the 'single line' system, each outlet of the gated pipe was fitted with a valve. These valves were grouped into a suitable number and controlled from a central location to achieve a surge flow pattern. Mostafazadeh-Fard et al. (2006) designed an automatic surge flow irrigation system using wireless, cheap programmable surge valves installed in a gated pipe and use solar-powered batteries. The control mechanism consisted of an electronic board, motor and gear, and solar battery. Notwithstanding the merits of the surge system, the method is generally seen as complex and the cost of implementation may be too high.

Cablegation is an automatic furrow irrigation technique which uses a travelling plug inside a gated pipe system on a sloped headland. The slope causes the water application to be restricted to only those gates nearest to the plugs, and the flow into any furrow gradually decreases as the plug moves further downstream (Figure 2.10). Although cablegation has a number of advantages including labour savings and potential reduction in runoff, it was found to be unable to compensate for the furrow-to-furrow variability in intake rate (Kemper et al. 1987). Cablegation systems have not experienced significant adoption mainly because of their complexity.

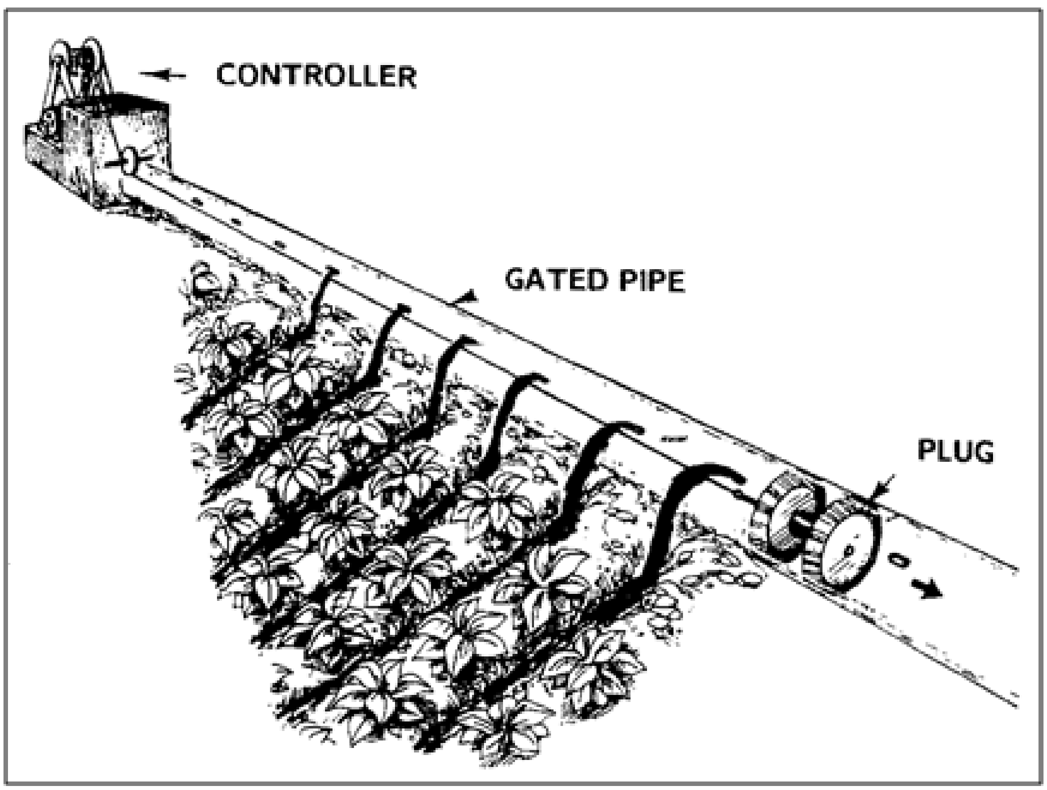


Figure 2.10: Cablegation system

(source: Kemper et al. 1987)

An automatic cutback furrow irrigation system was described in Humpherys (1971). In this system, the initially high furrow inflows are automatically 'cut back' or reduced by lowering the depth of water in the supply ditch resulting in a more uniform water application. Water is distributed to individual furrows through metal or plastic tubes installed in the side of the concrete-lined ditch.

The drawback of this design is that it is a fixed system and is likely to interfere with the operation of machinery near the edges of the field. The mechanism of lowering the flow in the ditch is also likely to be complex and expensive to implement in larger commercial fields.

AWMA's Aquator (AWMA 2009) and RUBICON's FarmConnect^{TM} (RUBICON 2011) systems are commercial automatic surface irrigation systems currently used in Australia. The basic features of the two systems are similar and include:

- the use of the SCADA platform and software installed in a computer,
- the use of wireless radio telemetry for communication among the different system components,
- a wide range of devices that can be monitored and controlled (for instance bay gates, soil moisture sensors, flow meters and water pumps), and
- the use of solar power in the remote devices to be controlled.

With the use of either of these systems, an irrigator would for example be able to switch on a pump, open a bay gate, acquire soil moisture data and automatically switch off the inflow from a remote location. And with the use of the internet, the irrigation could potentially be controlled from anywhere in the world. FarmConnect^{TM} can graphically display the farm being irrigated by use of satellite mapping and GPS positioning.

2.7.3 Feedback control systems

Feedback control in automated bay and basin irrigation systems typically involves the use of sensors placed near the downstream end of the field (for example: Clemmens 1992, Niblack & Sanchez 2008, Humpherys & Fisher 1995). The sensors are triggered by the advancing water front to send a signal by telemetry to the gates to cut off the flow (Niblack & Sanchez 2008, Humpherys & Fisher 1995). Feedback from sensors can also be used to continually adjust the flow rate (Clemmens 1992).

The use of a water sensor feedback control system (Humpherys & Fisher 1995) was applied in the semi-automation of basin and border irrigation. The design allowed the signal from the sensor (when the water front arrived at this point) to be sent via infrared telemetry to the electric solenoid which controlled the irrigation. On the other hand, Niblack & Sanchez (2008) designed an automated basin irrigation using commercially available products. The flow of water into the border was controlled by gates powered by a battery connected to a solar panel. The system applied both time-based and volume-based control. The cut-off distance portion of the system used commercial radio transmitters placed along the border to transmit a signal to the gate to close and for the next gate to open. These transmitters were triggered by the advancing front of water.

The above sensor-feedback systems were relatively cheap since they mainly used commercially available components. In addition, field tests undertaken demonstrated their potential for labour savings. However, the major drawback of the use of water sensors is that they have to be removed before machinery is used on the farm. Also, in these two methods control was purely by time/distance to cut off, and no attempt was made to estimate the soil infiltration characteristics.

2.7.4 Automatic real-time optimisation and control systems

The computerised furrow irrigation automation system utilising an adaptive control algorithm (FACC, Figure 2.11) was designed by Hibbs et al. (1992). In this system, water is delivered to a block of furrows and the inflow rate is monitored while the outflow from selected furrows is monitored using a flume and a depth sensor installed near the downstream end of the field. The inflow system employs an adjustable pressure regulator and a diaphragm valve to supply equal inflow rates among a block of furrows. The outflow rate from the selected furrows is periodically determined once the water front has reached the downstream end of the field. The infiltration characteristics are then analysed by a microcomputer running a volume balance model and the inflow is adjusted (cutback) accordingly using an automatic valve. The basis for the optimisation of the irrigation is the desired outflow rate. In comparison with the conventional furrow irrigation, trials under the FACC system resulted in 95% reduction in sediment discharge, 74% reduction in runoff and an increase of 39% in application efficiency.

It is worth noting that control in the FACC system is effected after the completion of the advance. The flume and the depth sensor are also installed close to the downstream end of the field. The system was tested in a field with relatively short furrows (maximum of 122 m). However, in Australia relatively long furrows (some in excess of 1000 m) are commonplace and in some cases optimal irrigation performance is achieved by terminating the inflow before the water front has reached the downstream end. Even in cases whereby optimal performance is projected to occur after the completion of the advance, it may still be too late to achieve effective control of the irrigation given that the flume and depth sensor are installed close to the downstream end of the field. In addition, the system is based on the outflow hydrograph, and it is not always practical to obtain accurate measurements of outflow using a flume. This outflow is only monitored from selected representative furrows, and while it might be infeasible to monitor

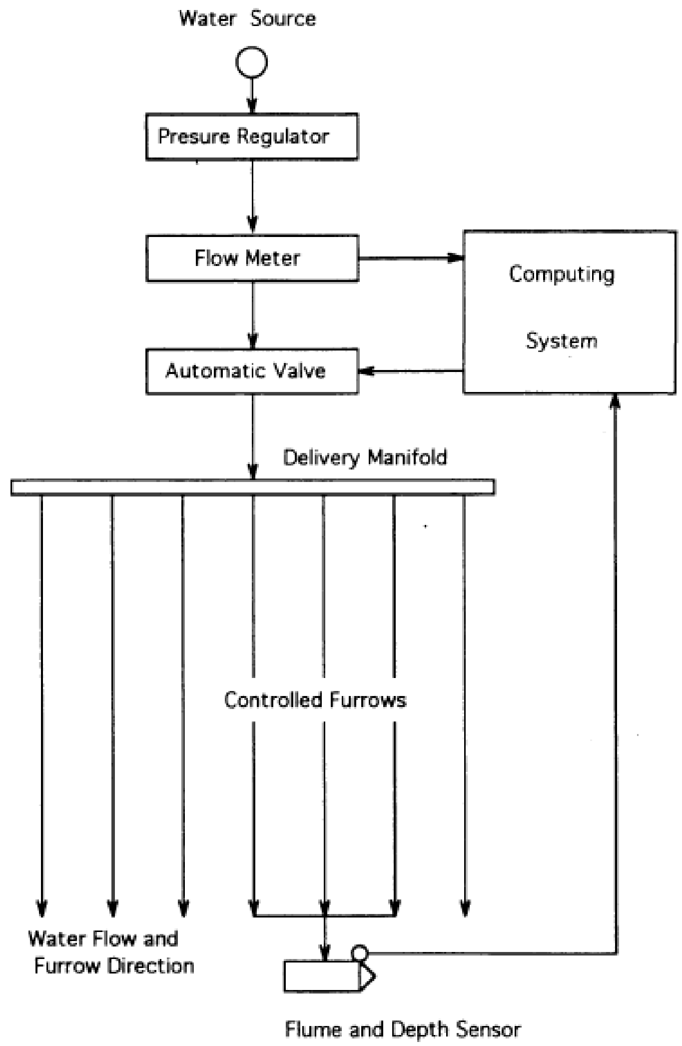


Figure 2.11: FACC irrigation system

(source: Hibbs et al. 1992)

outflow from each furrow, errors will inevitably be introduced into the system because of spatial variability of the infiltration characteristics across the field.

The advance rate feedback irrigation system (ARFIS) is an automated furrow irrigation system designed by Latimer & Reddell (1990) that uses advance data at two known points along the length of the furrow in the volume balance model to estimate the soil infiltration characteristics in real time. These characteristics are used to determine the appropriate time to cut off flow and the reduction in inflow (or cutback) necessary to achieve a desired net average infiltrated depth. The communication between the system components (computer, water sensors and the flow control system) was via radio or infrared telemetry. This system was found to be more profitable than the conventional furrow irrigation systems. However the sensing of water at two points along the length of the furrow and the variable flow control system is likely to add into the complexity and initial cost of ARFIS.

Emilio et al. (1997) developed the infiltration parameter estimation (IPE) simulation model for real-time control of furrow irrigation. The model determines the soil infiltration characteristics from measured advance data using the kinematic wave model, and uses the cutback (reducing inflow rate) concept to optimise the irrigation on the basis of a desired infiltrated depth. The IPE model takes into account the spatial and temporal infiltration variability resulting in a more accurate estimation of infiltration distribution (Emilio et al. 1997). However, the initial cutback is effected after the completion of the advance phase. Therefore as noted with the FACC system above, it may be too late in some instances to achieve optimal irrigation performance if the advance phase has to be completed before inflow is terminated.

The AIM model (which is also based on the kinematic wave model) was used in the IIC (intelligent irrigation controller) in a trial at an automated border-check farm in Dookie, Northern Victoria (Dassanayake et al. 2001). The system consisted of a network of probes and sensors which transmitted data in real time to a central computer. The data was used in the AIM model to determine the optimal irrigation time based on the required infiltrated depth. This is a relatively new development in surface irrigation, but initial results suggest average water saving of about 38% over conventional methods is potentially realisable. The data presented by the authors however suggest that the AIM model has a poor prediction of advance.

A furrow irrigation system which estimates the soil infiltration characteristics in real time, performs simulation and optimisation and determines the appropriate time to cut off while the irrigation is underway was proposed by Khatri & Smith (2006). The system involves:

- determination of a model infiltration curve from extensive evaluations;
- measurement of inflow to each furrow (or group of furrows);
- measurement of the advance at one point midway down the furrow;
- estimation of the infiltration characteristics of the trial furrow by scaling from the parameters of the model curve; and
- simulation and optimisation (based on maximising the application efficiency) of the irrigation to determine the optimum time to cut off flow.

This approach was selected in this dissertation as the basis for the design of a furrow irrigation system utilising adaptive real time control on the basis of its simplicity. The detailed procedure is described in Chapter 3.

2.7.5 Discussion

Out of the automated surface systems discussed in this chapter, 'Aquator' and 'FarmConnect^{TM}' are probably the only systems that have received significant adoption especially within the dairy industry (for the irrigation of pasture) in the southern parts of Australia. Others (for example surge flow, cablegation and automatic cutback) are fairly old systems but there is no evidence of their recent use. The FACC, ARFIS, IPE, and AIM systems were trialled in research environments but to the best knowledge of the author, there have not been applied in commercial settings. The concept proposed by Khatri & Smith (2006), and which forms the basis for the development of the real-time optimisation and control system discussed in this dissertation, has never been implemented in the field.

The entire review in this chapter and in particular on automated surface systems, has demonstrated the need for the design and development of a new furrow irrigation system simple enough to encourage adoption and yet capable of delivering significant labour savings and improved irrigation performance. This will now be detailed in the next chapter.

2.8 Conclusions

This chapter has presented a review of automation, control and optimisation of surface irrigation and in particular furrow irrigation.. It has shown that the initial attempts focussed on the automation of mainly the water delivery system for the main purpose of reducing the high labour requirements of these methods. As technology improved and as people became more aware of the need to ensure sustainable use of water resources with environmental conservation in mind, the need to develop water efficient systems became more imperative.

Overall there has been more work done in basin/border systems than in furrow system. This is because the former are more amenable to automation and control than the latter. Gates that are normally used as inlets to basins/orders can easily be automated. A wide variety of these gates are manufactured in Australia and are widely available. Automation of the siphon method, which is commonly used in the furrow system, is perhaps technically infeasible. There is a potential to automate gated pipe, PTB and bank-less channels application methods.

SIRMOD and WinSRFR are probably the two most widely used tools for the simulation and optimisation of surface irrigation systems. These models typically use historical data to modify future irrigations. A number of simulation models have been developed in Australia and especially at the NCEA. The SISCO model has proved to be a suitable basis for the development of a simulation model automatic real-time optimisation and control

The approaches to automation, optimisation and control of furrow irrigation discussed above have performed fairly well in research settings and demonstrated potential labour savings and increased water use efficiencies. However none of the methods to date has been widely adopted by irrigators. This may have to do with the initial costs of these systems and their perceived complexities. It is therefore concluded that there is a case for the design and development of a simple, robust and reasonably priced automatic control and optimisation system for furrow irrigation.

Chapter 3

Design of system

3.1 Introduction

A system for real-time optimisation and control of furrow irrigation is described in this chapter. The system estimates the soil infiltration characteristics in real time and utilises the data to control the same irrigation event to give optimum performance for the current soil conditions. This essentially overcomes the effects of spatial and temporal variations in infiltration characteristics, potentially leading to a significant improvement in irrigation performance (as demonstrated by: Raine et al. 1997, Smith et al. 2005, Khatri & Smith 2007). To encourage adoptability, the system has been kept simple: the inflow rate is fixed with the irrigation being controlled by varying the time to cut off. The hardware and software components of the system are described in this chapter. A new software package, AutoFurrow, was developed and integrated with the hardware components. Communication among the system components is via wireless radio telemetry.

3.2 Real-time optimisation and control

3.2.1 Infiltration variability

Infiltration is the process through which water enters into the soil. Infiltration rate is controlled by several physical and chemical properties of the soil, the most important of which are texture, structure, initial moisture content, organic matter, surface sealing and irrigation water quality. Typically the infiltration rate for initially dry soil is high, and decreases gradually to a fairly steady rate.

It has been widely established that variability in infiltration occurs both temporally and spatially (for example: Walker 1989, McClymont & Smith 1996, Emilio et al. 1997, Gillies 2008). In the case of furrow irrigation, the soil infiltration characteristics thus vary along as well as across the furrows. Spatial variability is primarily attributable to the differences in the soil physical and chemical properties while temporal variability may be as a result of soil moisture differences and farming operations (for example zero tillage and soil compaction due to wheel traffic and irrigation).

Infiltration variability is particularly significant in furrow irrigation since furrows serve both as a means of conveying water across the field and as a surface through which infiltration occurs. In practice infiltration variability causes non-uniformity in water absorption rates and furrow stream advance rates (Trout 1990). 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 and runoff from the downstream end. Trout (1990) and Gillies (2008) concluded that infiltration variability significantly reduces irrigation water use efficiency. Achievement of higher irrigation performance in furrow irrigation is further compounded by the furrow-to-furrow inflow variability from both gated pipes and siphon tubes Trout & Mackey (1988).

3.2.2 The concept of real-time optimisation and control

The practical implication of the temporal infiltration variability is that the soil infiltration data obtained at any particular time of the season may not be accurate enough for use in the hydraulic simulations to predict irrigation performance for future irrigations. Similarly, inter-furrow infiltration variability may limit the use of the soil infiltration characteristics obtained from a single furrow in the rest of the field.

Real-time optimisation of individual furrows has been proposed for the management of spatial and temporal infiltration variability (for example: Emilio et al. 1997, Mailhol & Gonzalez 1993, Khatri & Smith 2006, Turral 1996). In this approach the soil infiltration characteristics are estimated, analysed and used to optimise the same irrigation event to give optimum performance for the current soil conditions.

A number of simulation studies have quantified the potential improvement in irrigation performance achieved through real-time optimisation and control. For instance, Raine et al. (1997) evaluated 17 surface irrigation events in the Burdekin Delta and demonstrated that application efficiencies could potentially be improved from a mean of 41% to 93%. On the other hand, Khatri & Smith (2007) showed that the total volumes of water applied to two furrow-irrigated fields (with a total of 44 irrigation events) in southern Queensland could be reduced by 20% and 60% respectively.

As stated above, the primary aim of real-time optimisation and control is to improve the irrigation performance. Optimisation is undertaken according to a specified objective function which may vary in complexity. A simple objective function for instance may involve maximising the application efficiency subject to a desired minimum requirement efficiency. More complex ones may involve specifying the target application, distribution and requirement efficiencies, and the minimum depth, drainage and runoff. This however might possibly complicate and reduce the robustness of the system. Optimisation is undertaken using a simulation model usually by adjusting the time to cut off the inflow so as to satisfy the objective function selected. In addition to the time to cut off, more complex optimisation strategies may involve adjusting the flow rate part way through the irrigation event.

As explained in Chapter 2, previous systems developed for real-time optimisation and control of furrow irrigation have performed reasonably well in research settings but none so far has proved to be commercially viable. Most of these systems have been perceived to be too expensive and generally too complex. To encourage adoption, a real-time optimisation and control system would need to have:

- a simple control strategy;
- minimum sensing;
- a robust and accurate simulation model; and
- a simple optimisation strategy.

The basis for this type of system was proposed by Khatri & Smith (2006) who hypothesised that the shape of the infiltration characteristic for a particular field or soil is relatively constant despite variations in the magnitudes of the infiltration rate or depth of infiltration. The amount of data required for the prediction of the soil infiltration characteristics are reduced by scaling the infiltration parameters from an infiltration curve of known shape (model infiltration curve) and one advance point measurement in the furrow. The scaling procedure will be described in greater detail later in this chapter.

3.3 System description and operation

3.3.1 Introduction to system implemented for the field trials

The major aim of this PhD project was to develop, prove and demonstrate an automated real time optimisation and control system for furrow irrigation. As already explained, a number of automation hardware are available commercially and their development was outside the scope of this project. Hence what was actually implemented for the field trials may be slightly different from the system that would be rolled out in a commercial setting. It was envisaged from the onset of the project that if the trials proved successful, then a commercial angle would be pursued in the future.

To achieve the objective of the project, it was necessary to integrate an appropriate simulation model with the associated automation hardware. The system developed (Figure 3.1) consists of five main components:

- a water delivery system,
- an inflow measurement system,
- a water sensor to monitor advance of water along the furrow,
- computing system, and
- a radio telemetry system to facilitate communication among the system components.

Water is supplied into a group of furrows from gated pipe, PTB or siphons, and the flow rate is determined through inference from pressure measurement using a PST. The signal output (current) from the PST is then converted to pressure head. The pressure head is ultimately converted into flow rate using an appropriate equation (such as the standard orifice equation, Eqn. A.4, Appendix A). Other flow measurement techniques can also be used, including flow meters that may be incompatible with the telemetry system. However in the latter case flow data would have to be entered manually into the computer model.

When the water front reaches the water sensor placed approximately midway down the furrow, a signal is sent via radio telemetry to the computer (could potentially be stationed in a remote location) which then calculates the current infiltration characteristics. Based on the user-defined optimisation strategy, the model determines the optimal time to cut off the inflow and displays the predicted performance measures and other variables. The use of the real-time optimisation system in the field is preceded by a comprehensive characterisation of the field to determine the model infiltration curve. The procedure followed in the field trials is summarised in Figure 3.2 and discussed below.

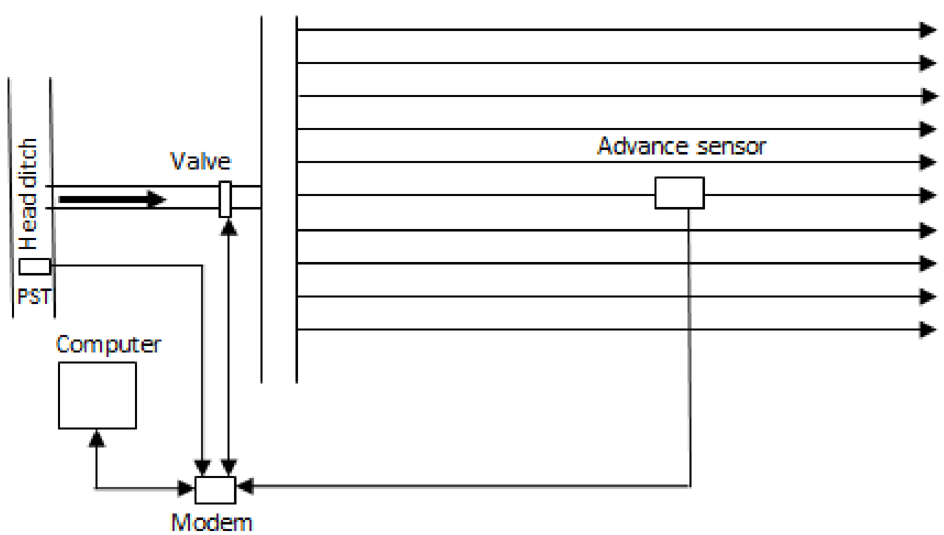


Figure 3.1: Automatic real time control system for furrow irrigation

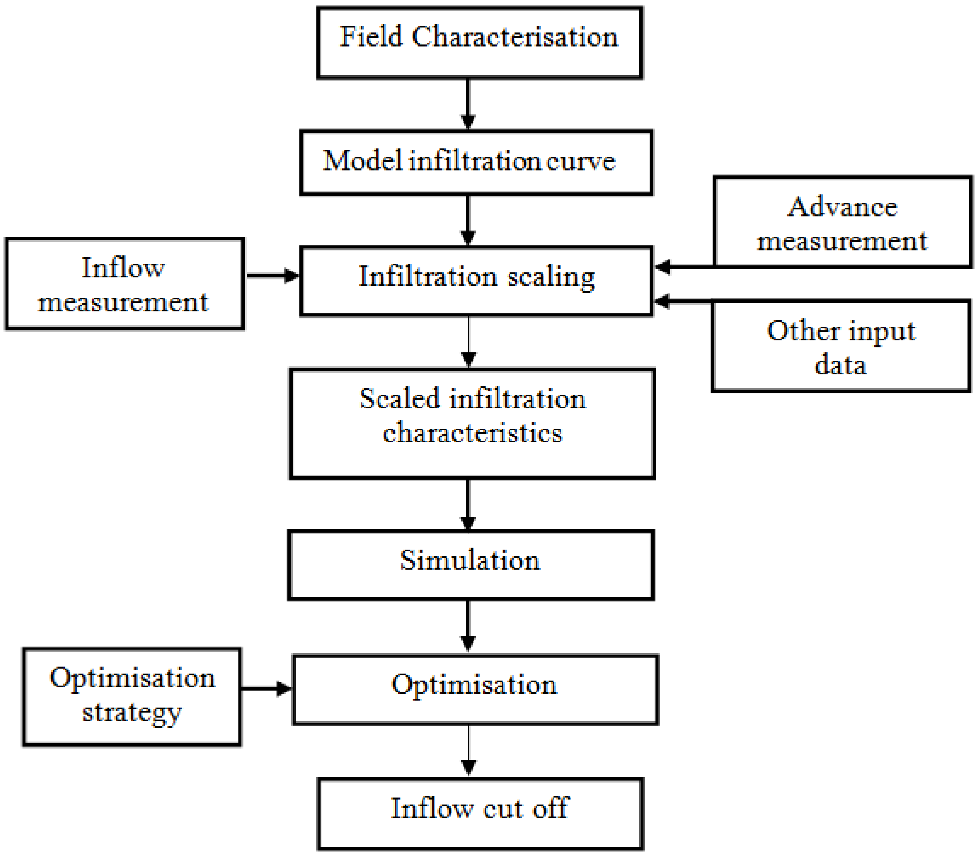


Figure 3.2: Basic real-time optimisation and control system

3.3.2 Field characterisation

The use of the real-time optimisation and control system in the field is preceded by an initial comprehensive evaluation to determine the model infiltration curve. This is achieved by selecting a representative furrow in the field and evaluating it over an irrigation event. The representative furrow was selected randomly from the set of furrows chosen for evaluation, but excluding the wheel-trafficked furrows as they would, on average, have faster advance rates than the non-wheel-trucked furrows. The following data is collected during the evaluation process: advance and runoff data; furrow geometry (top width, middle width, bottom width and maximum height); inflow; furrow length; and field slope. The Irrimate^{TM} advance sensors can be used to monitor the advance of flow along the furrows. This initial evaluation is also important in determining the optimum flow rate to be used later in the irrigations controlled by the optimisation system.

The data collected is used in hydraulic simulation models such as IPARM (Gillies & Smith 2005) or SISCO (Gillies et al. 2010) to calculate the soil infiltration characteristics (see Section 4.5 for an illustration). These models identify the infiltration parameters through an inverse solution; the parameters are incremented until the model reproduces the measured water advance. These parameters are then used in the Kostiakov-Lewis equation (Subsection 2.4.2, Eqn. 2.4) to obtain the model infiltration curve. An example of how to generate infiltration curves is shown in Table B.26.

3.3.3 Water delivery and inflow measurement system

In furrow systems using the siphon and PTB application methods, a head or supply ditch typically runs perpendicularly to the furrows along one edge of the farm. In the case of the gated pipe method, the water source may be a head ditch or a riser drawing water from an underground pipe. The system developed in this study is applicable to all these different water application methods. At the present stage of the project, the opening and closing of the valve that supplies water to a group of furrows is achieved manually (Figure 3.1). However, as already explained in Chapter 2 (subsection 2.2.3) of this dissertation, there is a potential to automate this process (particularly for the PTB and layflat application methods) in future designs using techniques that have been used successfully in surface systems (for example: AWMA 2009, Latimer & Reddell 1990). An automated bay outlet which can potentially be used in furrow irrigation is shown in Figure 3.3 below.

Total inflow into a group of furrows is measured through inference from measurement of pressure using a pressure sensitive transducer (PST). For both the siphon and PTB methods, the PST is installed in the head ditch to measure the

Figure 3.3: Automated bay outlet (Rubicon Water Publicity brochure)

effective pressure head (Figure 3.4), and in the bottom of the gated pipe in case of the gated pipe application method. Prior calibration of the PST is required in all cases, and an appropriate equation is used to convert the effective pressure head into flow rate per furrow. Regardless of the water delivery method in use, the flow rate is continuously monitored by the PST and the data relayed to a computer. In this project model LS-10 PST manufactured by WIKA Australia PTY Ltd. was used. It has an output range of 4 to 20 mA and a pressure range of 0 to 0.25 bar. The PST was calibrated for pressure measurement in the laboratory before being used in the field. As already explained, other conventional metering devices may also be used, and can be easily interfaced with the chosen telemetry system. Inflow data may also be manually entered into the computer model if the results from the PST are questionable.

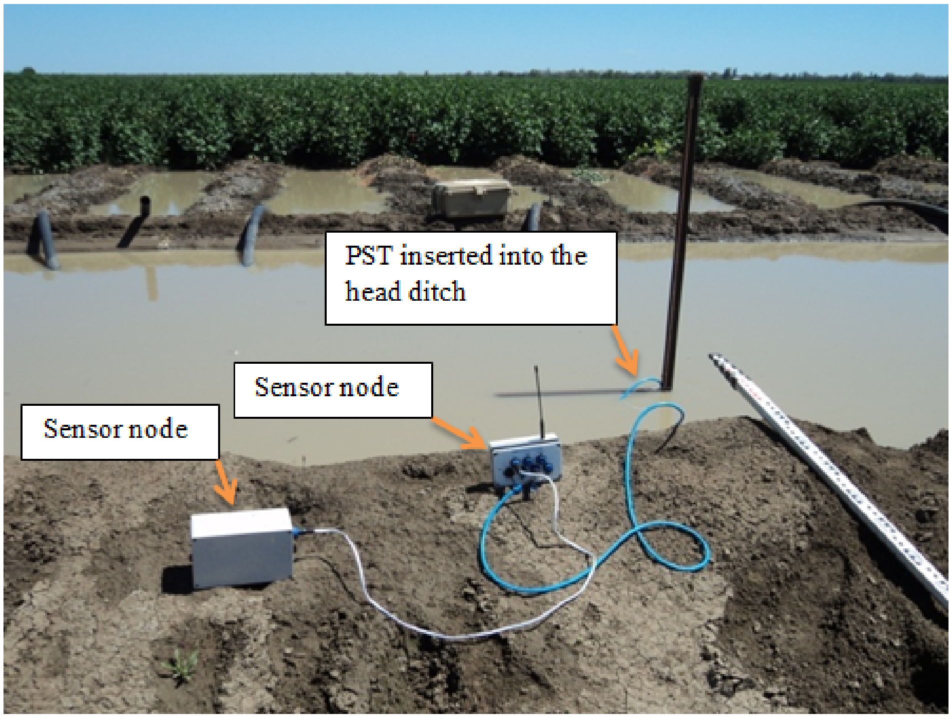


Figure 3.4: PST inserted into the head ditch

In the siphon application method, the measured effective pressure head is converted into discharge using the Eqn. 2.1 (section 2.2 of Chapter 2) proposed by Bos (1989). A value of 0.019 is assumed for the friction factor f as proposed by Wigginton (2008) for use in siphons operating in field conditions. Further calibration is possible with secondary measurement of siphon flows. The PST was subsequently re-calibrated in the field to measure discharge from a PTB using an ultrasonic flow meter strapped around the PTB and applying the Bernoulli equation between the head ditch and the discharge point:

$$\frac{p_1}{\rho g} + \alpha \frac{{v_1}^2}{2g} + Z_1 - h_f = \frac{p_2}{\rho g} + \alpha \frac{{v_2}^2}{2g} + Z_2 \tag{3.1}$$

where p_1 is the pressure in the head ditch (N/m^2); v_1 is the velocity in the head ditch (m/s); Z_1 is the elevation of the PTB in the head ditch (m); ρ is the density of water (1000 kg/m^3); h_f is the head loss due to friction (m); p_2, v_2, and Z_2 are the corresponding values at the discharge point of the PTB; and α is the velocity head coefficient. Since the velocity of water in the head ditch v1 is very small, the term ${v_1}^2/2$g will be negligible in comparison to other terms and may be ignored.

In the initial stages of this project, large diameter gated flexible fluming was seen as a feasible alternative to siphons, PTB and bankless channels for the delivery of water in furrow systems. This was mainly because of its potential to offer uniform furrow inflows when designed using the hydraulic program GPIPE (Smith 1990, Figure 3.5).

However, as will be explained in the next chapter, the field sites that were available to undertake the trials were all under siphon and PTB methods. Nonetheless, hydraulic experiments of large diameter gated flexible fluming were undertaken in the Hydraulics laboratory at USQ (Appendix A). It is anticipated that this work will provide a good basis for the application of gated flexible fluming to automated furrow systems.

For discharge through a flexible gated pipe, the program GPIPE can be used to produce a look-up table of pressure head versus flow rate using the characteristic equation (Eqn. 3.2) for the Bartlett gate (arising from laboratory experiments conducted on gated flexible fluming - Appendix A).

$$Q = 7.9621{H_p}^{0.4994} \tag{3.2}$$

where Q is the discharge through the outlet (l/s), and H_p is the pressure head immediately upstream of the gate (m).

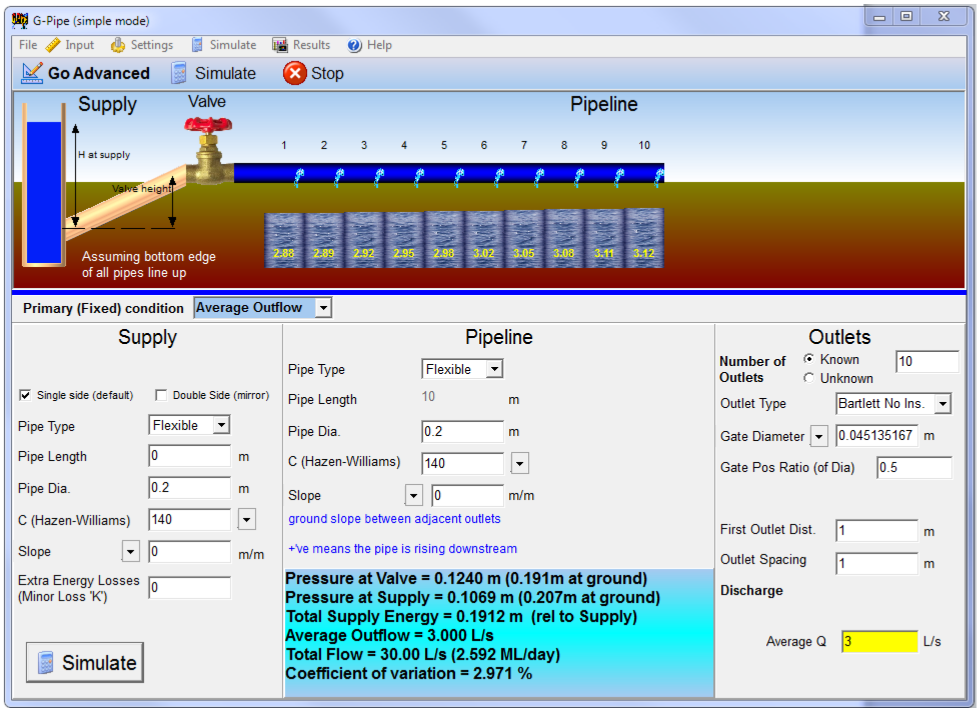


Figure 3.5: The GPIPE program main interface

3.3.4 Advance sensing

An advance water sensor placed along a selected furrow is used to detect the arrival of the water front (Figure 3.6). In the present study the sensor was placed approximately midway down the selected furrow. The sensor consists of a two-wire cable, the ends of which are exposed. The sensor is triggered by the arrival of the water front which completes the circuit, and a signal is sent to the computer. In the present design the sensor is used to monitor only one furrow, but more furrows can be monitored with the addition of cables. The monitored furrow is selected after an initial evaluation on the basis of being the most representative in the irrigation set. In addition it is possible to use a longer cable and hence the other components of the sensor can be stationed outside the field.

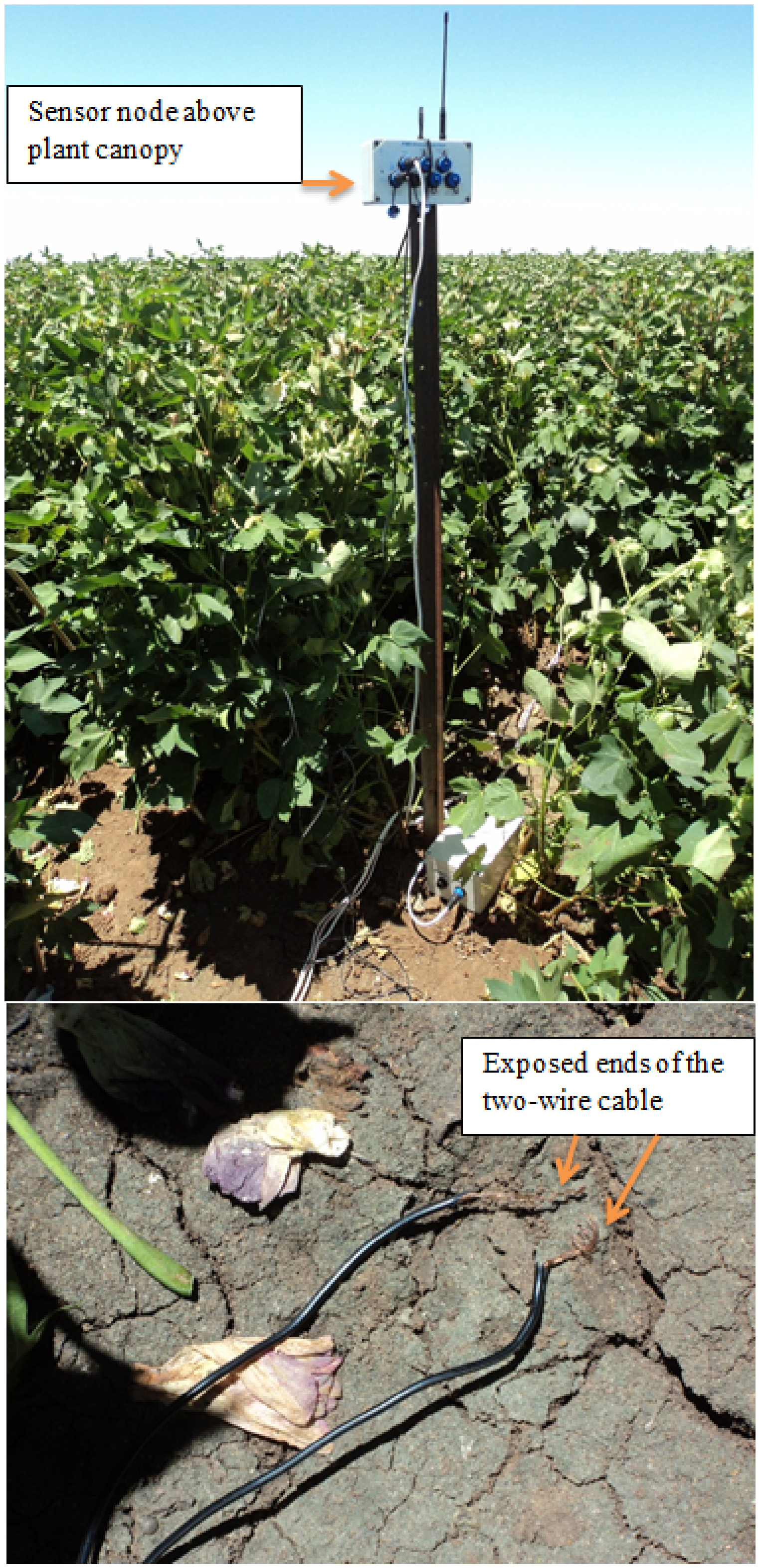


Figure 3.6: Advance meter attached to sensor node)

3.3.5 Infiltration scaling

Apart from the model infiltration curve, inflow and advance measurement, field data (length, furrow spacing, and slope) and furrow dimensions are required to perform infiltration scaling. The acquisition of the inflow and advance distance data for scaling has already been explained above. As stated above (Subsection 3.3.1), the shape of the infiltration curve (Eqn. 2.4, subsection 2.4.2) is expected to remain relatively constant throughout the irrigation season. Hence the model infiltration curve can be used as a reference point in determining the infiltration characteristics of the rest of the furrows and for future irrigation events. There are two methods that have been proposed for the determination of the scaling factor for each furrow.

In the scaling technique proposed by Khatri & Smith (2006), only one point in the advance curve is used implying that less data is required. This approach is based on the application of the Kostiakov-Lewis equation (Eqn. 2.4) and the volume balance model as used by Elliot & Walker (1982):

$$Q_o t = \sigma_y A_o x + \sigma_z k t^a + \frac{f_o t x}{1+r} \tag{3.3}$$

From the re-arrangement of the above equation, Khatri & Smith (2006) formulated a scaling factor (F) for each furrow:

$$F = \frac{Q_o t - \sigma_y A_o x}{\sigma_z k t^a x + \frac{f_o t x}{1+r}} \tag{3.4}$$

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 shape factor taken to be constant (0.77);

and σ_z is the sub-surface shape factor and is defined as:

$$\sigma_z = \frac{a + r(1-a) + 1}{(1+a)(1+r)} \tag{3.5}$$

where r is the exponent from the power curve advance function $x = p(t)^r$ for the model furrow (Raine & Smith 2007); a, k, f_o are as defined before (subsection 2.4.2) while p and r in the advance function are parameters fitted via regression. A close scrutiny of the scaling factor F (Eqn. 3.4) shows that it is the ratio between the infiltrated volume as calculated by the volume balance method in the trial furrow and the infiltrated volume as calculated by the parameters of the model infiltration curve (Khatri & Smith 2006).

However, since the above method uses a single advance point to calculate the scaling factor, an error in the measurement of this point will impact on the results. An alternative approach for calculating the scaling factor was proposed by Gillies et al. (2010) and has been incorporated into the SISCO model. Here instead of a direct solution the scaling factor is determined through a process of least squares analysis. The final scaling factor is determined as that which minimises the difference between the measured and modelled advance points and/or depths. This new method uses the full hydrodynamic model and can utilise any number of points in the advance curve to undertake the scaling.

The scaling factor obtained from either of the two approaches is then applied to the Kostiakov-Lewis equation (Eqn. 2.4) to obtain the scaled infiltration curves for the whole field:

$$I = F(k\tau^a + f_o\tau) \tag{3.6}$$

where I_s is the scaled infiltration (m^3/m); a, k, f_o and are as defined earlier. In effect both parameter k and f_o are scaled in the same proportion while parameter a is assumed to be constant.

The scaled infiltration characteristics obtained from this approach are then used in the new software developed (described in subsection 3.3.7) to simulate and optimise the irrigation process and to determine the optimum time to cut off the inflow.

3.3.6 Software package developed

A new software package, AutoFurrow, was developed in this study and integrated with the hardware components to control furrow irrigation in real time. As explained in Chapter 2 (subsection 2.5.4), the software developed uses the SISCO simulation engine. SISCO simulation engine was chosen because of its robustness and also because its code was accessible through the NCEA, hence the necessary modifications and integration could easily be undertaken.

Variables to be specified by the user in main screen of the software (Figure 3.7) include: field length, furrow spacing, field slope, Manning n and the furrow dimensions (top width, middle width, bottom width and maximum depth). The model curve infiltration parameters (a, k, f_o and r) obtained from one or more evaluations as well as the irrigation deficit are also specified. AutoFurrow can either use continuous flow (inferred from the continuous pressure head monitoring using a PST or from any other flow meter) or average flow. A look-up table of flow versus pressure entered into the software by the user is used for the determination of the continuous flow data.

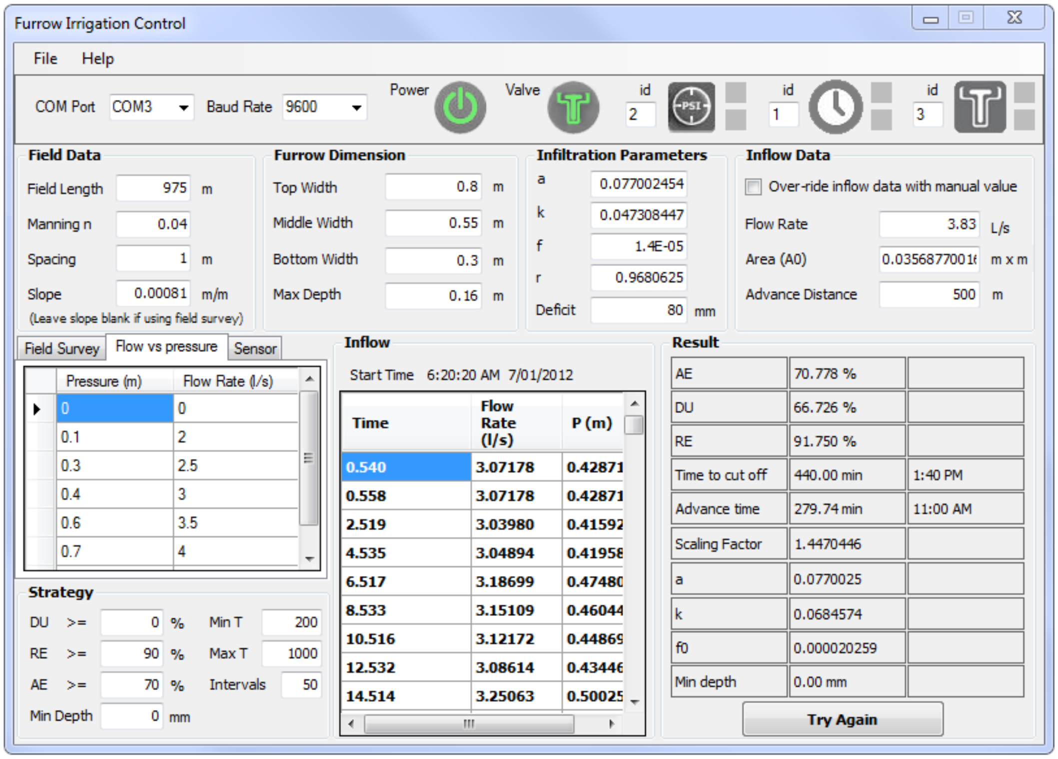


Figure 3.7: AutoFurrow main input screen

3.3.7 Computing, telemetry system and simulation

A computer was selected as the controller of the automatic furrow irrigation system because of the need for sufficient capacity to run a hydrodynamic simulation model and at the same time process data received from the PST and the water sensor. EeePC 1001PX was chosen for use in the study on the basis of its long battery life and light weight. A solar-powered battery was provided as a backup power source during the trials (Figure 3.8). The computer model developed for this system is described later in this chapter. The process of optimisation is discussed later in the chapter.

The telemetry system relays to the computing system the continuous flow data from the PST and the time the water front arrives at the water sensor. The telemetry system used was a license-free radio frequency of 900 MHz with a transmission distance of approximately 2 km. The system was originally developed for use in pressurised irrigation systems (McCarthy et al. 2008) but was

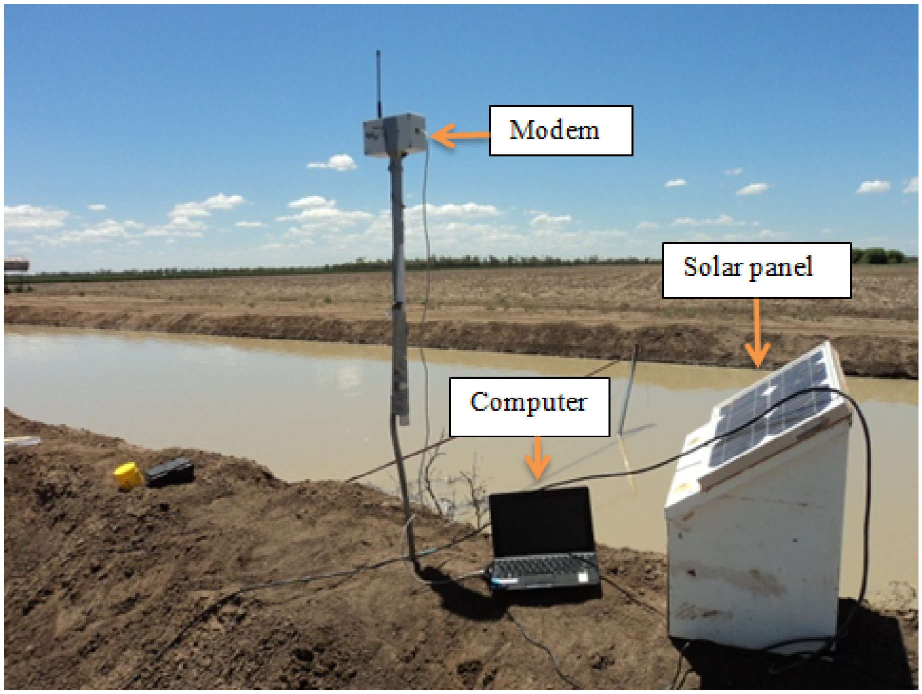


Figure 3.8: Computer, modem and solar panel)

modified and used in this project. It consists of a sensor node powered by a 12 V battery (Figure 3.4). Each sensor (PST and the advance sensor) is connected to a node with a unique identification number (ID). Communication between the sensors and the computer is through a 'Zigbee' modem manufactured by Digi International. The modem is connected to the computer through a USB connection and does not require an external power source (Figure 3.8). The sensors and the modem are programmable. The codes on the sensor nodes and the modem were written in C and ASCII languages respectively to facilitate communication between the sensors and the computer.

The nodes continuously log and save data from the sensors, and at a chosen interval these signals are relayed to the computer via wireless radio telemetry. Alternatively the data can be uploaded directly to a computer using a serial connection to link the node to the computer. The nodes can accommodate varying lengths of antennae for maximum transmission of the radio waves. These waves are line-of-sight propagated, implying that the sensor nodes must have a direct line of sight to the modem for communication to occur (Figures 3.6 and 3.8).

For the purpose of scaling the model infiltration parameters, the distance from the inlet to where the advance water sensor is positioned (advance distance) must be specified (Figures 3.7). Whether using continuous or variable flow data, the measured flow up to this point in time is used in the scaling process. In order to simulate the irrigation performance the model uses all of the available continuous inflow data but assumes that the inflow rate continues into the future at a rate equal to the average flow.

3.3.8 The optimisation process

AutoFurrow determines the measures of irrigation performance over a range of times to flow cut-off selected by the user (Min T and Max T, Figure 3.7). However, to converge on a single time to cut off the user needs to specify the optimisation strategy. As explained earlier, the strategy may be varied and may include one or a number of the common measures of performance (that is, application, distribution and requirement efficiencies and minimum depth of infiltration).

The software selects the first cut-off time (minimum) to meet these conditions as the optimal time to cut-off. The selection of these minimum values often involves a compromise among the various measures of irrigation performance. A higher time to cut off for instance may improve DU and RE but lower the AE (and vice versa). The optimisation strategy was made flexible in AutoFurrow as different irrigators are known to have different preferences.

The main output of the optimisation process is the optimal time to cut off the inflow. This must fall between the desired minimum and maximum cut off times specified beforehand in the main input screen. AutoFurrow will also determine, at that particular time to cut off, the AE, DU and RE. The optimisation can be recalculated at any time by varying the input variables and pressing the button

'Try Again' in the main input screen. This is especially important where no optimal solution is obtained (model fails to converge) at the selected optimisation strategy.

3.4 General discussion

The real time optimisation and control system designed to be tested in field in this study is based on the system proposed by Khatri & Smith (2006). The authors evaluated the system mainly using data obtained from two cotton fields within southern Queensland. The assumptions inherent in this approach including other factors which could potentially impact on the field trials are discussed below.

3.4.1 Infiltration scaling process

The scaling technique applied in this method is based on the volume balance model (Eqn. 3.4). The underlying assumption made is that the shape of the infiltration characteristic for a particular field or soil remains relatively constant despite variations in the magnitudes of infiltration rate or depth of infiltration. Consequently, parameter 'a' in Eqn. 3.4 is assumed constant. Evaluations undertaken by Khatri & Smith (2006) showed a good correlation between the infiltration curves obtained from the complete set of advance data and those calculated using the scaling technique.

The infiltration scaling process is vital to the success of the real time optimisation system. It would thus be useful to confirm the accuracy of the process using data sets from fields potentially with different soil types.

3.4.2 Model infiltration curve

Simulations undertaken by Khatri (2007) suggested that the choice of the model furrow (from which to obtain the model infiltration curve) did not significantly alter the scaled infiltration curves. Hence the model furrow could be picked arbitrarily from among those considered to be possessing representative characteristics. As with the infiltration scaling process discussed above, it would be necessary to validate this assumption using diverse data sets potentially exhibiting more spatial and temporal infiltration variation.

It is apparent in Eqn. 3.4 that since parameter 'a' is assumed constant in the scaling process, the shape of the scaled infiltration curves will be similar to that of the model infiltration curve. Therefore it is important to select a model infiltration curve which is representative of the field to be evaluated using the real time optimisation system. Selection of the model curve may be a complicated process if the furrow sets to be evaluated possess distinctively varied infiltration curves. The model infiltration curve under the system discussed in this chapter has a significant impact on its performance.

3.4.3 Selection of the advance distance

The system designed in this chapter estimates the soil infiltration characteristics, optimises the irrigation and determines the preferrred time to cut off the inflow in real time (while the irrigation is underway). Therefore the advance time (to the advance distance used in the scaling process) should be within the the preferred or optimum time to cut off.

The potential effect of the advance distance on the predicted infiltration (using the scaling procedure) has been evaluated by Khatri & Smith (2006) and Langat et al. (2008). In both studies, scaling factors were calculated at different advance points along the length of the furrows. The study by Khatri & Smith (2006) found that the scaling factor varied along the length of the furrow in no particular order. However for most furrows the scaling factors increased with distance beyond the furrow midpoint. A similar variation in scaling factors was found in the work by Langat et al. (2008), but the study showed that the variation was a function of the shape of the advance curve. This study also concluded that on average, the prediction of the infiltration curves is improved when the advance distance corresponding to the furrow halfway point or later is selected, and that points early in the advance may result into significant loss of accuracy. In both studies, the scaling factors tended to converge to a constant value.

Neither of the above studies (or any other published literature to the best knowledge of the author) attempted to quantify the effect of the advance distance on the performance of furrow irrigation under real time control. The field trials on the proposed system are expected to generate data that can be used for this purpose, and consequently give practical guidelines on the selection of the advance distances.

3.5 Summary

A system for real-time optimisation and control of furrow irrigation was developed in this study. The soil infiltration characteristics of the present irrigation are predicted using the scaling technique which uses the infiltration parameters of a model curve. A new software package, AutoFurrow, was developed and integrated with the hardware components. The inflow and advance measurement have been automated at the present stage of the project. The computerised system utilises wireless radio telemetry for communication among system components.

Chapter 4

Evaluation methodology

4.1 Introduction

The previous chapter provided a detailed description of the newly developed system for furrow irrigation which optimises furrow irrigation automatically and in real time. The present chapter describes how both the hardware and software components were tested at a field sites in St George and Dalby, Queensland, Australia. In addition to the testing, the procedure used to evaluate the actual performance of each irrigation is presented. In total 11 trials were undertaken involving both siphon and PTB water delivery methods.

4.2 Field sites

4.2.1 2010/11 season

Trials for the real time adaptive control system developed in this study were undertaken in the 2010/11 irrigation season at a commercial furrow-irrigated cotton property in St. George, south-western Queensland Australia (coordinates 28 °C 2′2.51″ S, 148 °C 34′ 54.5″ E). Like in most major cotton growing areas in Australia, the predominant soil in this area is the cracking clay soil or black Vertosol. As the name suggests, this type of clay soil is characterised by deep cracks when dry.

Climatic online data available at the Australian Government's Bureau of Meteorology (BoM) website (http://www.bom.gov.au/climate/data/) show the 15-year (1997-2011) mean annual rainfall data for St. George (Station Number 043109) was 528.2 mm. The corresponding mean maximum and minimum annual temperatures were 27.8 and 13.8 °C. Cotton farming is thus largely dependent on irrigation and being a relatively hot area, irrigation water is typically applied after every 9 days. The cotton irrigation season normally starts in September and ends in March. In the 2010/11 however, slightly more than the 15-year mean rainfall was received in this area especially between September and December (Figure 4.1). This therefore reduced the need for irrigation and hence limited opportunities to undertake the field trials. Field trials were further complicated by the severe floods that occurred in much of Queensland, St. George region included.

In terms of water application methods the cotton property was divided into two: one site using siphons while in the other using the pipe-through-the-bank (PTB) application method (Figure 4.2). The furrow lengths were measured to be 714 and 970 m in the siphon and PTB irrigated furrows respectively using a hand-held GPS distance measuring device. Furrow spacing was 1 m in both cases. The

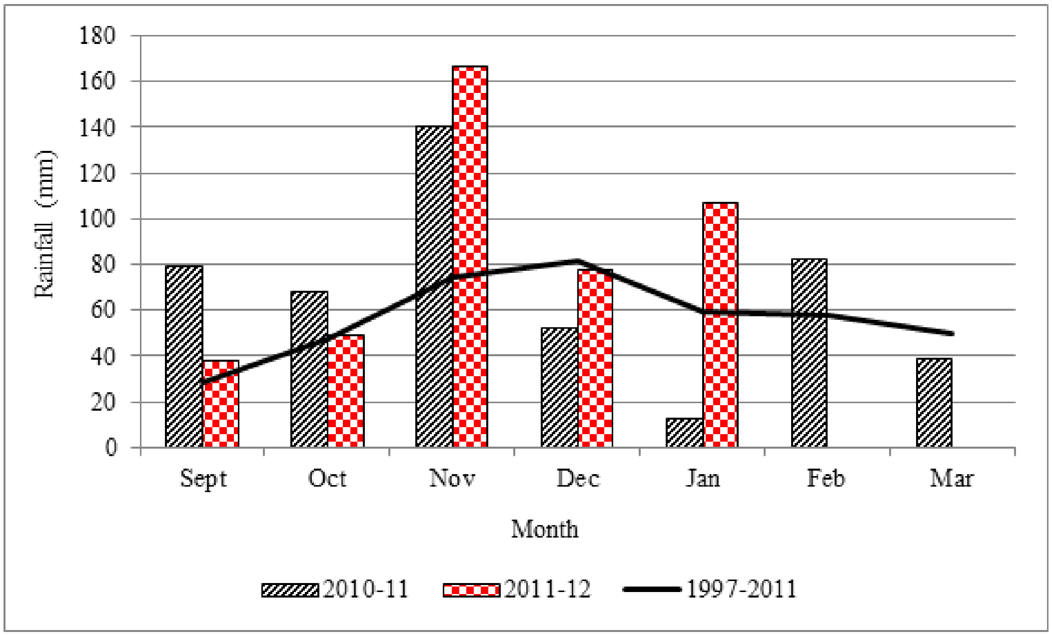


Figure 4.1: St. George rainfall patterns (BoM Station Number 043109)

detailed furrow geometry was undertaken using a ruler and a spirit level. The entire cotton property had been recently laser-levelled, and the slope in the trial site was determined using a dumpy level to be 0.07% (0.0007 m/m).

(a) Siphon method (b) PTB method

Figure 4.2: Water application methods at the trial site

4.2.2 2011/12 season

The 2010/11 St George field site was used again in the 2011/12 irrigation season trials. However a different set of furrows was selected and by this time only PTB were used by the irrigator to supply water to irrigation furrows. These set of furrows were 975 m long and the slope was determined to be 0.081%. As was the case in the previous irrigation season, the rainfall was higher than normal (Figure 4.1). Ironically, the area was again hit by flooding which severely impacted on the field trials.

A second field site in Dalby (coordinates 27 °C 10′ 59.8836″ S, 151 °C 15′ 49.4166″ E) was used in the 2011/12 irrigation season to undertake the trials. The predominant soil type in the commercial property is grey Vertosol which swells when wet and develops huge cracks when dry. Only siphon water application method was used at this site. The furrow spacing was 2 m and the furrows were 600 m long. The furrow slope was determined using a dumpy level to be 0.08%. The Dalby area also received a large amount of rain in January/February 2012 thereby limiting the opportunities for field trials.

4.3 Automated real time optimisation trials

All the four trials at the PTB site were controlled using the automated real time optimisation system as opposed to only one in the siphon site during the 2010/11 irrigation season. The other trials in the siphon site were controlled according to the normal farmer practice. All irrigations (in both sites) were controlled in the 2011/12 irrigation season. The methodology used in these trials has been broken into the following components:

- inflow measurement;
- advance monitoring; and
- telemetry system and hydraulic modelling.

4.3.1 Inflow measurement

In both the siphon and the PTB application method water is drawn from the head ditch. A PST was selected for this project because of the desire to obtain continuous flow data to be used in the real time control software. This involved inserting the PST into the head ditch to monitor the effective pressure head which was in turn converted into discharge using an appropriate equation (Subsection 3.3.3).

The PST had been calibrated in the Hydraulics Laboratory at USQ for use in the 2010/11 trials; however field calibration was necessary in order to adjust the theoretical head-discharge characteristic for field conditions. The calibration exercise involved placing the PST into the head ditch at the same level as the water discharged into the field. A metal pole was used to anchor the PST into the head ditch and the levels were obtained using a dumpy level. The assumption at the time of the calibration exercise was that both the PTB and the siphon would have unsubmerged draining conditions, in which case the head measured using the PST would be the effective head driving the flow.

The effective head was converted into flow rate using Eqn. 2.1 (Subsection 2.2.2 of Chapter 2) in the siphon calibration exercise while Eqn. 3.1 (Subsection 3.3.3 of Chapter 3) was used in the case of the PTB. An ultrasonic flow meter strapped around the siphon and the PTB provided accurate discharge for the calibration process. In both cases (siphon and PTB methods) a look-up table comprising of pressure head and flow rate was determined based on the corresponding equations and the field calibrations. The tables were then copied into the AutoFurrow software and used in the evaluation of the optimisation system.

The calibration exercise was undertaken with only a limited number of PTB and siphons operating. However during the actual trials with a larger number of these conduits in use, it was discovered that both the siphons and the PTB had submerged discharge conditions. Submerged discharge conditions meant both the level of water in the head ditch and at the discharge points varied simultaneously, implying that the head measured by the PST was not the effective head. Hence although the intention was to use variable flow in the trials, average flow (obtained using the ultrasonic flow meter was used instead.

Towards the end of the 2010/11 trials a pontoon designed by a local consultant (Justin Schultz) was used to measure effective pressure head. The pontoon was made of hollow plastic pipe and was placed in the pool of water in the discharge point (Figure 4.3). Its light weight enabled it to float. A vertical pipe was attached to the pontoon and closed at the bottom. The PST was then placed in this pipe from the top. A thin pipe was used to draw water from the head ditch into this pipe through an opening at the bottom. The resulting pressure head measured by the PST was the difference in water levels between the head ditch and that within the field. The ability of the pontoon to float ensured that the effective head was being recorded by the PST. The device performed reasonably well at higher heads but at lower heads its floatability was hampered by limited water at the discharge points.

In the 2011/12 irrigation trials, an ultrasonic flow meter (Figure 4.4a) was used for inflow measurement at the St George site (PTB) while the Irrimate^{TM} siphon flow meter (Figure 4.4b) was used in Dalby trials involving the use of siphons. The flow data was then fed manually into the simulation model.

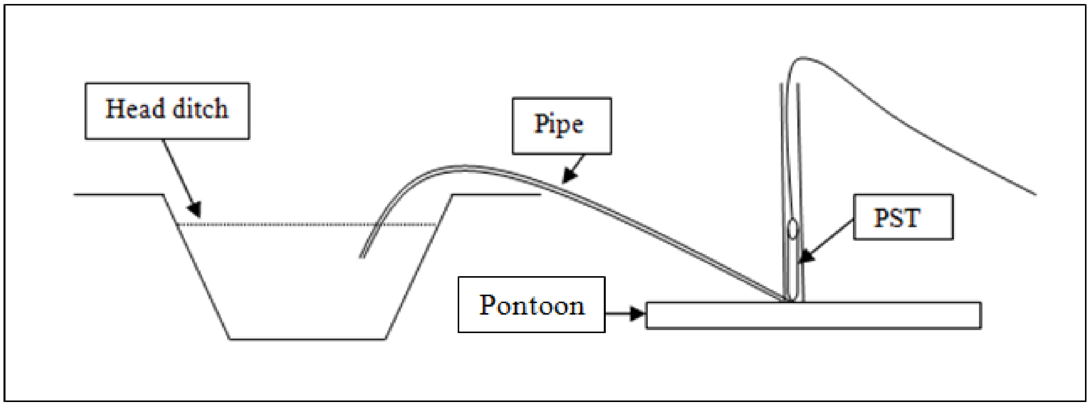


Figure 4.3: Pontoon used to measure effective head

(a) Ultrasonic flow meter

(b) Irrimate^{TM} siphon flow meter

Figure 4.4: Flow measurement tools

4.3.2 Advance monitoring

In the 2010/11 season, the advance meter was placed at a distance of 400 m and 500 m (from the inlet) in the siphon and PTB-irrigated furrows respectively. The same advance distance of 500 m was maintained in St George while 300 m was used as the advance distance in Dalby site during the 2011/12 trials. In effect the sensor was placed roughly mid-way down the furrow. This was selected to allow sufficient time to control the irrigation and also because earlier work has shown that placing the sensor closer to the inlet may result in a substantial loss of accuracy in the scaling process (Langat et al. 2008). The advance meter and the associated components (battery and telemetry unit) were set up and tested before the start of the irrigation.

4.3.3 Telemetry and hydraulic modelling

Each irrigation controlled using the adaptive real time control software was preceded by the installation and testing of the PST and the advance meter. An ultrasonic flow meter was also strapped to the conduit to measure flow. A solar-powered battery was used to supply power to the laptop computer (both the PST and the advance meter had separate batteries).

A new data file was created in the AutoFurrow software (described in Chapter 3) for each irrigation, which required the following inputs:

- Field data;
- Furrow geometry;
- Advance distance;
- Look-up table relating discharge to head;
- Irrigation deficit;

- Optimisation strategy; and
- The model curve.

The irrigation deficit and the optimisation strategy were decided upon in consultation with the farmer. The latter is however flexible and hence could be altered during the irrigation if the software (AutoFurrow) failed to reach an optimal solution. For the 2010/11 irrigation season trials, the model curve (model parameters a, k, f_o and r) for the first irrigation (Trial 1A) was obtained from the previous season's Irrimate^{TM} evaluations in the same field. Trials 1A and 1B provided model curve parameters for Trials 2A and 2B respectively, while for Trials 3A and 4A the model curves were chosen arbitrarily from previous evaluations in the same field. The source of the model curves for the 2011/12 trials is explained in Section 7.2. The program uses the Manning's equation to calculate the cross-sectional area of flow at the upstream end of the field (A_o). The complete evaluation process is illustrated with an example in the next section of this chapter.

As soon as the irrigation was started the AutoFurrow software (Figure 3.7) was also started by pressing the button 'Power' in the main input screen. This start time was recorded and could be viewed from the main screen. The signals from the PST were being received at an interval of two minutes and were also visible on the main screen. However, as explained in Subsection 4.3.1, after the start of the 2010/11 irrigation season a decision was made not to use the variable data from the PST. Average discharge was obtained from the ultrasonic flow meter and copied into the model instead. By checking the box at the right top corner of the screen, the program would overwrite the inflow data from the PST and use the manually specified inflow. In reality this actually never happened during the trials and will be discussed in the next chapter. In the 2011/12 trials the inflow data was measured using the ultrasonic flow meter at the St George site and Irrimate^{TM} siphon flow meter (Figure 4.4b) at the Dalby site and was subsequently manually copied into the computer model.

When the water front arrived at the sensor point, a signal was sent to the computer. The program recorded and displayed the total advance time to that point as well as the actual clock time. This triggered the program to start the simulations and optimisation and eventually display the time to cut off and the predicted performance measures. In a number of cases, the program would not converge because of the optimisation strategy selected. New simulations were initiated by adjusting the optimisation strategy (DU, RE, AE, minimum depth and minimum and maximum irrigation times) and pressing the button 'Try Again' in the input screen. The AutoFurrow optimisation window is shown in Figure 4.5. The irrigations were then terminated as per the preferred time to cut off flow determined by the optimisation system and the data saved in the same file.

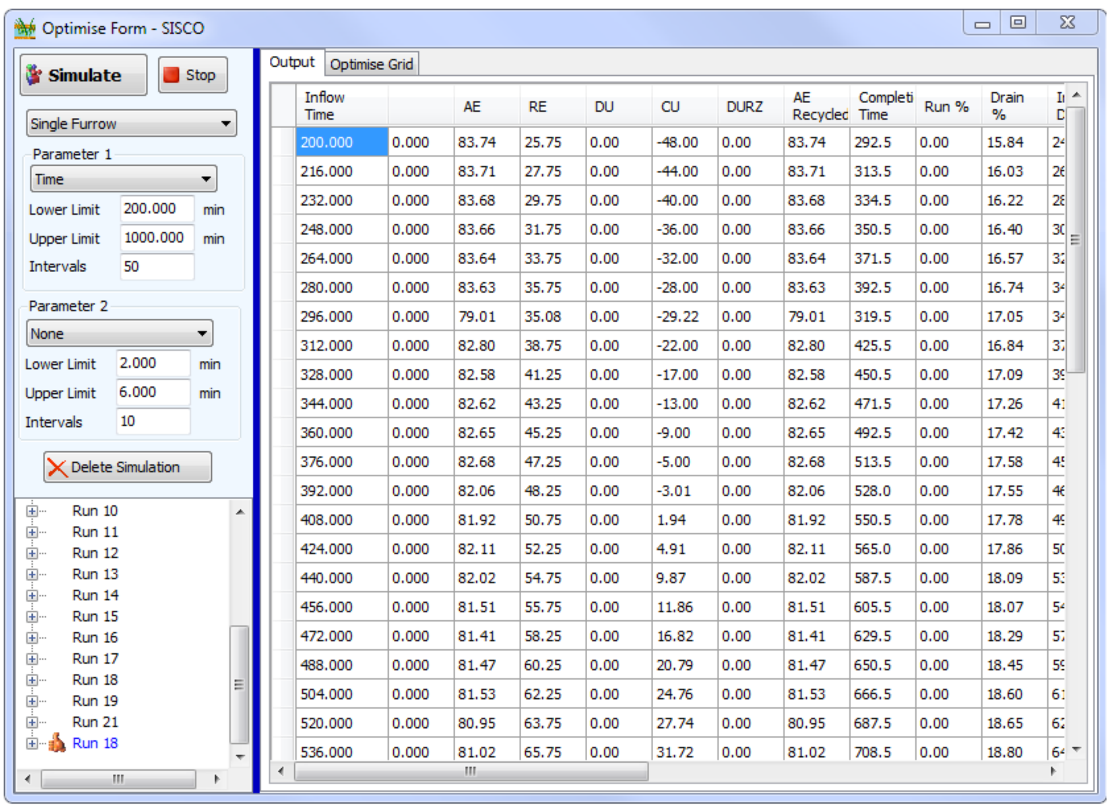


Figure 4.5: SISCO optimisation window

4.4 Evaluations based on full advance

The main purpose of the field trials was to test the optimisation system. As explained earlier, the system uses only one advance point approximately midway down the furrow and a scaling procedure to to estimate the infiltration characteristics of the soil from a known model infiltration curve. The complete advance data (and field details, inflow data and furrow geometry) were used to evaluate the actual irrigation performance, performance expected as per the farmer's management practices, multi-furrow performance and model infiltration parameters that could be used for next next irrigation. These evaluations are described below and will be illustrated with examples in the next section of this chapter.

4.4.1 Actual irrigation performance

Apart from testing the optimisation system, data was also collected to conduct a complete evaluation of the irrigation process using a procedure similar to the Irrimate^{TM} procedure described by Dalton et al. (2001). This evaluation was based on the complete advance data (in addition to other model requirements) and hence it has been referred to as 'actual irrigation performance' in this dissertation.

In general the procedure followed consisted of data collection from the field using the hardware tools (PST, ultrasonic flow meter and advance meters) which were then used in the SISCO hydraulic computer model in the process of simulation and optimisation. The PST was however not used in the 2011/12 irrigation season trials; flow rate was measured using an ultrasonic flow meter and Irrimate^{TM} siphon flow meter in the case of PTB and siphon respectively. Irrimate^{TM} evaluations were undertaken for each of the eight trials undertaken at the field site. Data collected during these evaluations were flow rate and advance data.

The Irrimate^{TM} advance meter (Figure 4.6) is 8 m long and consists of a similar number of sensors. This implies that for a field of furrow spacing of 1 m, a total of 8 advance measurements will be taken assuming that every row is watered. These meters were laid across the furrows at varying intervals along the length of the trial site. Between 5 and 7 advance meters were used in the trials (the exact number for each trial including the distances between the meters is illustrated in Appendices B and D).

Figure 4.6: Irrimate^{TM} advance meter

Field data collected were used in the SISCO model to undertake the process of hydraulic simulation of the irrigation. The process used advance and inflow data (in addition to furrow geometry and spacing, field slope and length, and Manning n) to determine the soil infiltration characteristics. It has already been pointed out that the SISCO model is self-calibrating, hence the program can be used to estimate the soil infiltration characteristics. Advance data from one model furrow was selected and used in this calibration process,with the assumption that the furrow is representative of the entire set of furrows. The model furrows selected were the same ones used in the automated real time optimisation trials described above. Alternatively, the infiltration data could be estimated using the IPARM model (Gillies & Smith 2005) and transferred to the SISCO model. The calibrated infiltration data were then used to simulate the irrigation and determine the performance. The main irrigation performance measures predicted were AE, DU, RE, inflow volume, drainage and runoff percentages.

4.4.2 Performance expected as per the farmer's management practices

The same data and procedure used above was used to evaluate the expected performance as per the farmer's management practices. This means that this evaluation was also based on data from the same one model furrow per irrigation. However, the time to cut off used was what would normally be used by the farmer and not necessarily what was used during that particular irrigation.

4.4.3 Multi-furrow evaluation

The complete advance data (eight furrows) collected during the evaluation process were also used to perform simulations for the entire set of the irrigation furrows, hereby referred to as multi-furrow simulation. This implies that as opposed basing evaluations on one model furrow as described above, calibrated infiltration data from the full set of furrows were utilised.

The procedure used in this study to perform multi-furrow simulation was proposed by Gillies et al. (2008a). In this method each furrow is simulated independently and the resultant profiles of applied depths are combined to evaluate the spatial irrigation performance. The methodology was initially implemented in the computer package IrriProb but has since been incorporated into the hydraulic simulation model SISCO (Gillies et al. 2010). Apart from simulations using the model furrow, the output of the multi-furrow evaluations included the combined performance of all the eight furrows monitored as well as individual performances of each furrow.

4.4.4 Model infiltration parameters for future irrigations

In some of the trials undertaken to test the optimisation system, model infiltration parameters were obtained from the immediate preceding irrigation. The infiltration data obtained from the model curve used in the actual irrigation evaluation above were used for this purpose. However, the AutoFurrow software required parameter r value (fitted parameter of the power curve advance function) which could not be obtained from the SISCO model. This parameter was thus estimated using the IPARM model (Figure 2.6).

4.5 Sample workings

Two examples will now be used to illustrate the evaluations based on the full set of advance data described above. The first example illustrates how the actual irrigation, performance as per the farmer's management practice and the model infiltration curve to be used for future irrigation were evaluated. The multi-furrow evaluation is illustrated in the second example.

Example 1

Firstly, Trial 3A (Chapter 5 and Appendix B) will be used to show how the actual irrigation was evaluated using a procedure similar to the Irrimate^{TM} process.

Step 1

The basic data used by the SISCO model as well as the furrow dimensions shown below were entered into the SISCO main input screen (Figure 4.7). The default value of Manning n (that is, 0.04) was used while free draining downstream conditions were assumed.

Date: 16/02/2011

Field length: 970 m

Slope: 0.0007 m/m

Inflow: 3.82 l/s

Furrow spacing: 1 m

Deficit: 82 mm

Table 4.1: Furrow dimensions - Trial 3A

Top width	800 mm
Middle width	600 mm
Bottom width	340 mm
Total depth	125 mm

Step 2

The complete advance data (8 furrows) is shown Table 4.2. Out of the 8 furrows monitored, Furrow 2 was selected as the model furrow because it was judged as the most representative. The performance evaluation of this set of furrows was based on this model furrow.

Table 4.2: Advance data - Trial 3A

	Furrow number							
	1	2	3	4	5	6	7	8
Distance (m)	Advance time (mins)							
0	1	1	2	1	1	0	0	0
250	104	152	168	169	116	75	74	58
500	252	265		313	292	213	186	135
650	332	354	422	353	358	288	291	179
800	389	413		413	436	346		217
920	480	493	510	510	503	389	403	276

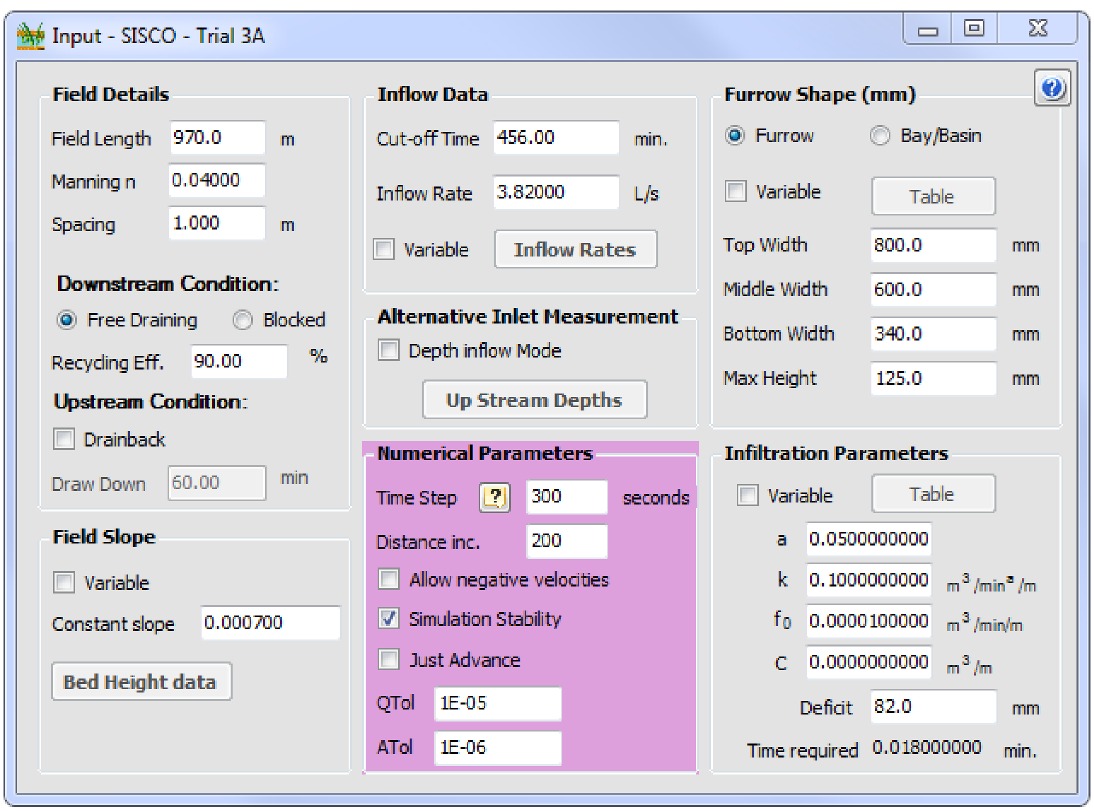


Figure 4.7: SISCO main input screen

Step 3

The SISCO model was used to determine the infiltration characteristics of the soil. The default infiltration parameters of the model are also shown in Figure 4.7. However since advance data was available, the model was used to obtain these parameters through a self-calibration process. The advance data from the model furrow (Table 4.2) were entered into SISCO and the calibration process undertaken. The calibrated infiltration parameters are shown in the left bottom part of Figure 4.8.

Figure 4.8: Calibration of infiltration parameters

Step 4

The calibrated infiltration parameters obtained in *Step 3* above were transferred into the SISCO main input screen (Figure 4.9) and the performance simulation undertaken (results displayed in Figure 4.10).

The method followed in evaluating the performance expected as per the farmer management practice was similar to the above, but a different time to cut off was used (normal farmer cut off time was used). In the above example, the normal time to cut off used by the farmer was 484 min. This was used in the SISCO main input screen instead of 456 min (Figure 4.9) and a new simulation was undertaken (Figure 4.11).

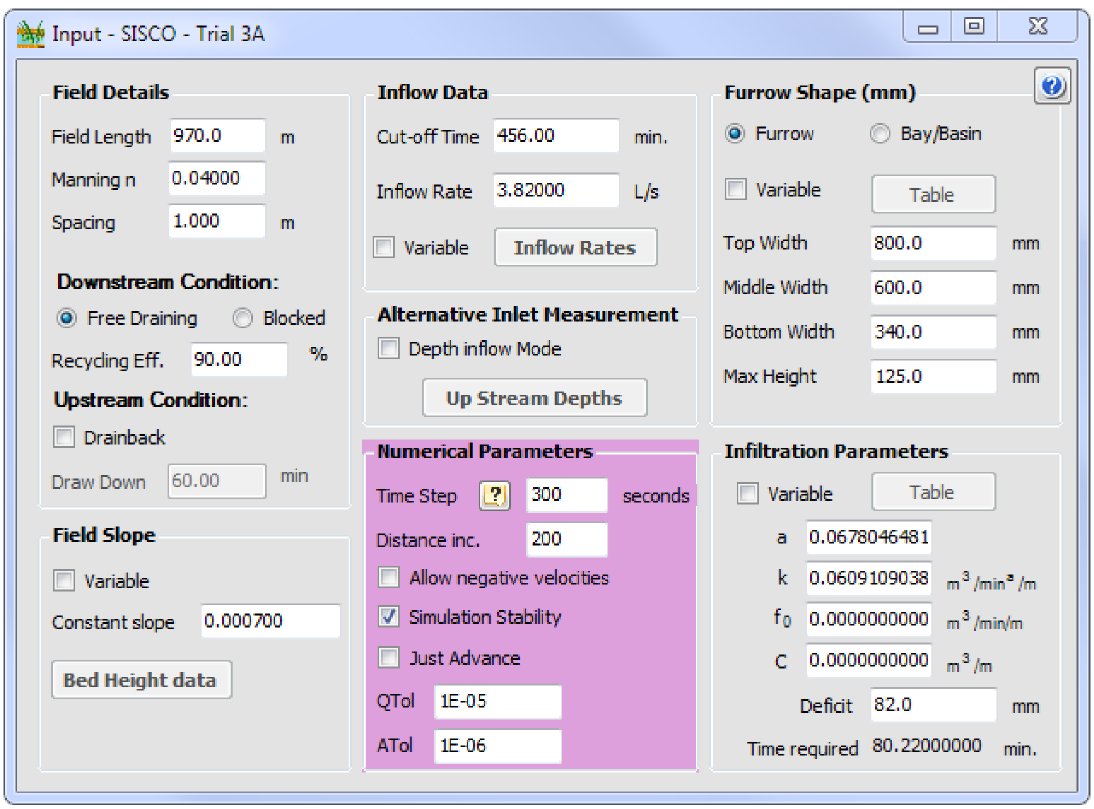


Figure 4.9: Infiltration parameters transferred to SISCO main input screen

The actual infiltration data obtained from one model furrow above could potentially be used as model infiltration data for future real time optimisation trials. However, to determine parameter r which is one of the inputs of the AutoFurrow software, the field data, furrow geometry and the advance data of the model furrow were entered into the IPARM model main user interface and a simulation initiated (Figure 4.12).

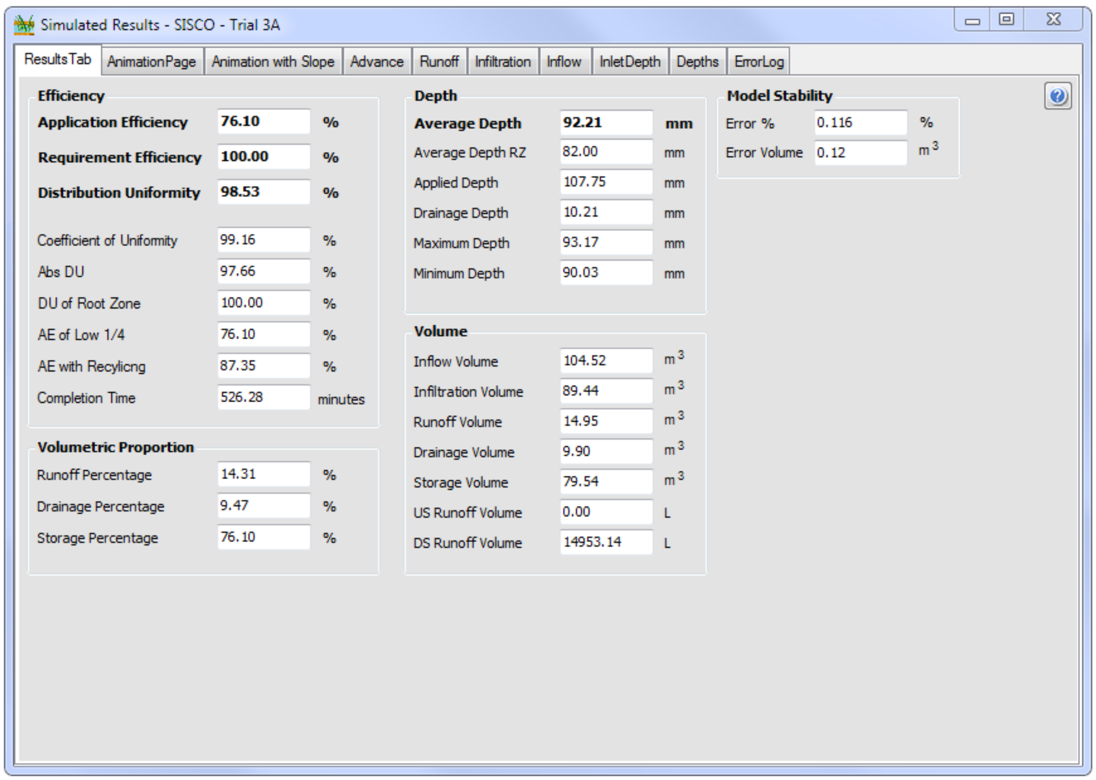


Figure 4.10: Results of evaluation

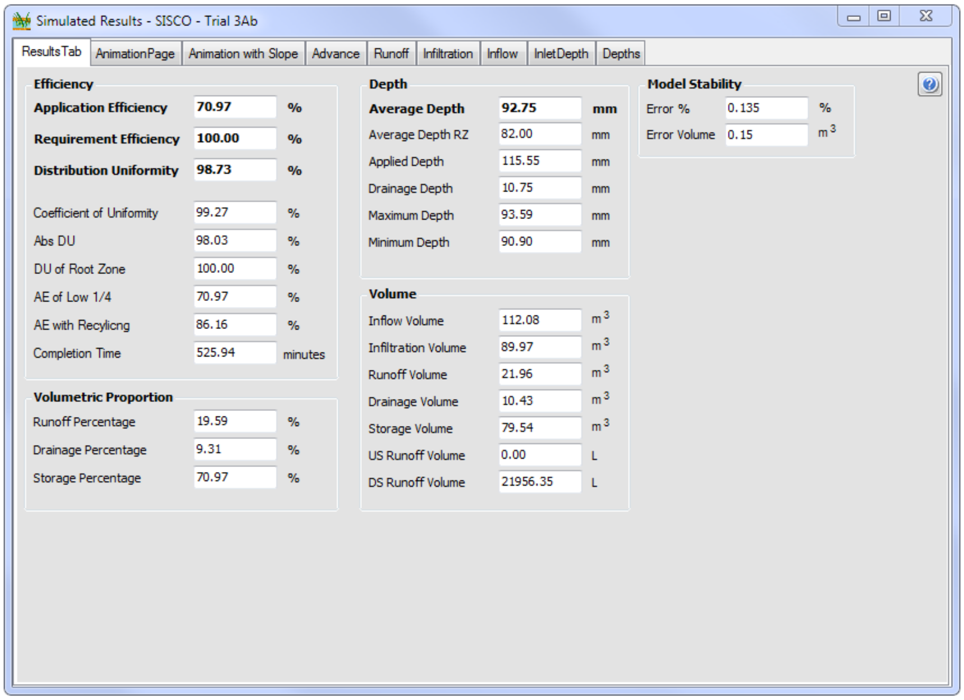


Figure 4.11: Performance as per farmer's time to cut off

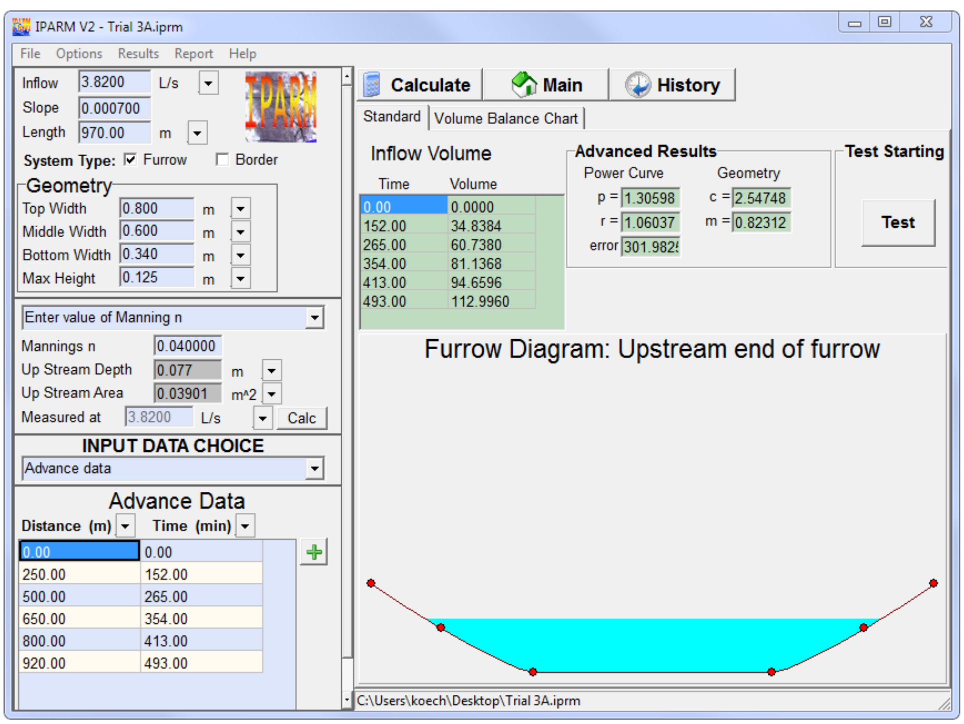


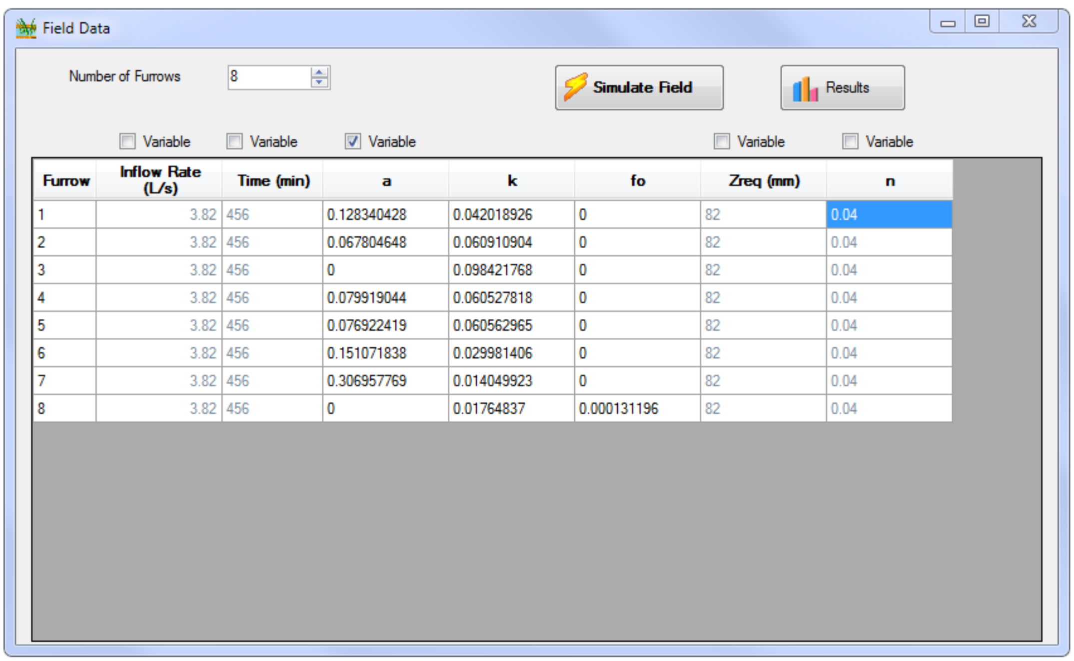
Figure 4.12: Determining parameter r using the IPARM model

Example 2

Trial 3A used above will also be applied here to illustrate how multi-furrow evaluation was undertaken. The procedure followed was as follows:

Step 1

The saved SISCO file for Trial 3A was opened. The multi-furrow input screen was opened and the infiltration parameters and other factors determined for each individual furrow during the actual irrigation evaluation were entered as shown in Figure 4.13.



Furrow	Inflow Rate (L/s)	Time (min)	a	k	fo	Zreq (mm)	n
1	3.82	456	0.128340428	0.042018926	0	82	0.04
2	3.82	456	0.067804648	0.060910904	0	82	0.04
3	3.82	456	0	0.098421768	0	82	0.04
4	3.82	456	0.079919044	0.060527818	0	82	0.04
5	3.82	456	0.076922419	0.060562965	0	82	0.04
6	3.82	456	0.151071838	0.029981406	0	82	0.04
7	3.82	456	0.306957769	0.014049923	0	82	0.04
8	3.82	456	0	0.01764837	0.000131196	82	0.04

Figure 4.13: Multi-furrow input

Step 2

Simulation of the irrigation was initiated by clicking on 'Simulate Field' (Figure 4.13). The SISCO model then calculated the performance for the combined set of furrows (Figure 4.14) and for each individual furrow (Figure 4.15). As shown in Figure 4.15, for this particular trial, the AE and RE were fairly consistent and hence reasonable results would have been obtained by selecting any of the furrows as the model furrow.

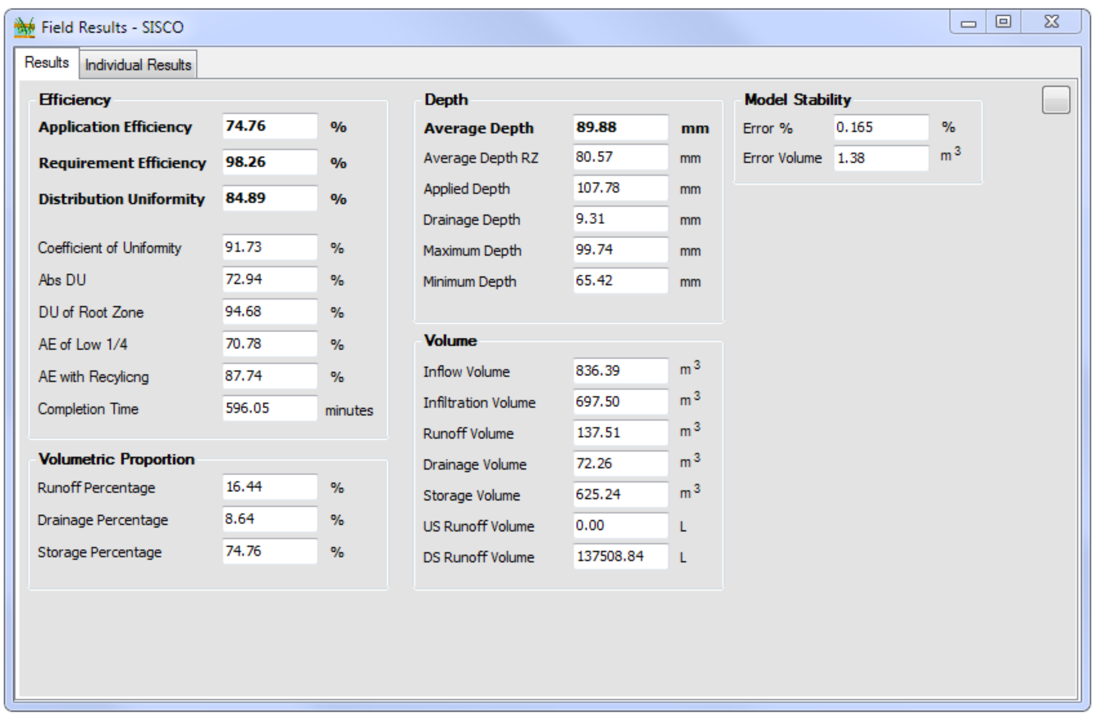
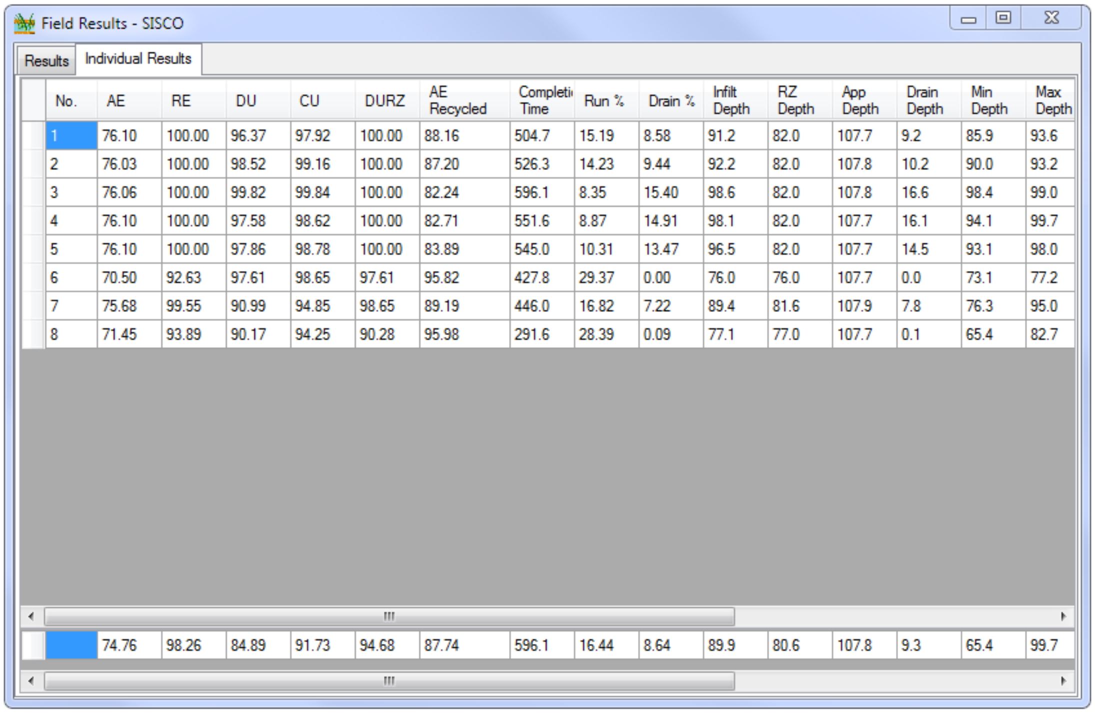


Figure 4.14: Combined results of entire set of furrows



Field Results - SISCO

Results | Individual Results

No.	AE	RE	DU	CU	DURZ	AE Recycled	Completi Time	Run %	Drain %	Infilt Depth	RZ Depth	App Depth	Drain Depth	Min Depth	Max Depth
1	76.10	100.00	96.37	97.92	100.00	88.16	504.7	15.19	8.58	91.2	82.0	107.7	9.2	85.9	93.6
2	76.03	100.00	98.52	99.16	100.00	87.20	526.3	14.23	9.44	92.2	82.0	107.8	10.2	90.0	93.2
3	76.06	100.00	99.82	99.84	100.00	82.24	596.1	8.35	15.40	98.6	82.0	107.8	16.6	98.4	99.0
4	76.10	100.00	97.58	98.62	100.00	82.71	551.6	8.87	14.91	98.1	82.0	107.7	16.1	94.1	99.7
5	76.10	100.00	97.86	98.78	100.00	83.89	545.0	10.31	13.47	96.5	82.0	107.7	14.5	93.1	98.0
6	70.50	92.63	97.61	98.65	97.61	95.82	427.8	29.37	0.00	76.0	76.0	107.7	0.0	73.1	77.2
7	75.68	99.55	90.99	94.85	98.65	89.19	446.0	16.82	7.22	89.4	81.6	107.9	7.8	76.3	95.0
8	71.45	93.89	90.17	94.25	90.28	95.98	291.6	28.39	0.09	77.1	77.0	107.7	0.1	65.4	82.7
	74.76	98.26	84.89	91.73	94.68	87.74	596.1	16.44	8.64	89.9	80.6	107.8	9.3	65.4	99.7

Figure 4.15: Individual furrow results

4.6 Summary

In this chapter, the field trials that were undertaken over two consecutive irrigation seasons principally to test the optimisation system (discussed in Chapter 3) are described. The complete irrigation evaluations (based on full advance data) conducted are also described. Measurement of effective pressure head in the head ditch using a PST proved technically difficult for submerged flow conditions at the discharge end. This is because the level of flow in the head ditch and the discharge points change simultaneously. A pontoon was later used but proved ineffective at lower pressure heads.

The chapter also described how the field data were analysed and evaluated mainly using the SISCO model. These evaluations were illustrated using two examples.

Chapter 5

Results of Preliminary Trials (2010/11 irrigation season)

5.1 Introduction

Field trials for the real time optimisation system for furrow irrigation described in the previous chapter were undertaken at a furrow-irrigated commercial cotton property in St George during the 2010/11 irrigation season. The cotton field utilised both the siphon and the PTB water application methods. One trial site consisting of 11 furrows was established at each of the two sections of the field. The trial sites established in the PTB and the siphon-irrigated sections are hereby referred to as Site A and Site B respectively. Four trials were undertaken at each site during the irrigation season. Each of the four trials at Site A was controlled as per the automated real time optimisation system (also referred to as 'optimisation system' in this dissertation) as opposed to only one at Site B. The rest of the trials in the latter site were controlled according to the normal farmer irrigation practice.

The data collected have been evaluated and presented in this chapter as follows:

- model curves and the scaled infiltration parameters used in the real-time optimisation software (AutoFurrow) discussed in Chapter 3;
- irrigation performance predicted by AutoFurrow; and
- complete irrigation performance evaluation comprising of one (model) furrow evaluation and performance expected as per the farmer's irrigation management practice.

The field results have been analysed and discussed in this chapter. The standard irrigation performance measures (AE, DU, and RE) as well as inflow, runoff and drainage have been used in the analyses.

It was, however, discovered during the data analysis stage that there was an error in the AutoFurrow code leading to the use of incorrect inflow rates during the control simulation; the program however used the correct inflow in the scaling procedure. This error was corrected in the subsequent version of the software and used to re-simulate the controlled irrigations while maintaining the same optimisation strategy as in the above trials for consistency

5.2 Scaling the infiltration

The model infiltration curves and the scaled infiltration parameters for each of the irrigations controlled by the optimisation system are shown in Table 5.1. These are based on the evaluations undertaken in the trial furrows (that is one furrow per trial).

Table 5.1: Model and scaled parameters

	Site A				Site B
Trial number	1A	2A	3A	4A	2B
Model curve					
a	2.26E-01	1.00E-07	1.10E-02	1.19E-01	5.11E-01
k	1.33E-02	8.15E-02	6.54E-02	4.73E-02	4.94E-03
f_o	0	4.16E-05	1.44E-05	0	0
Advance					
Distance (m)	500	500	500	500	400
Time (min)	177.26	245.05	265.36	341.64	395.46
Scaling factor	2.45	1.29	1.29	1.29	1.00
Scaled parameters					
a	2.26E-01	1.00E-07	1.10E-02	1.19E-01	5.11E-01
k	3.26E-02	1.05E-01	8.46E-02	6.09E-02	4.95E-03
f_o	0	5.35E-05	1.86E-05	0	0

The scaling procedure was undertaken using the method proposed by Khatri & Smith (2006) and encapsulated in Eqn. 3.4. This was discussed in detail in Chapter 3 (Subsection 3.3.5) of this dissertation. The scaling factor for the first irrigation controlled (2.45) was the highest, implying that the difference between the model and the measured infiltration parameters was the greatest among the controlled irrigations. This is possibly due to the fact that the model curve for this irrigation was obtained from evaluations undertaken in the previous irrigation seasons (as indicated in the above paragraph).

5.3 Predictions of the automated real time optimisation and control system

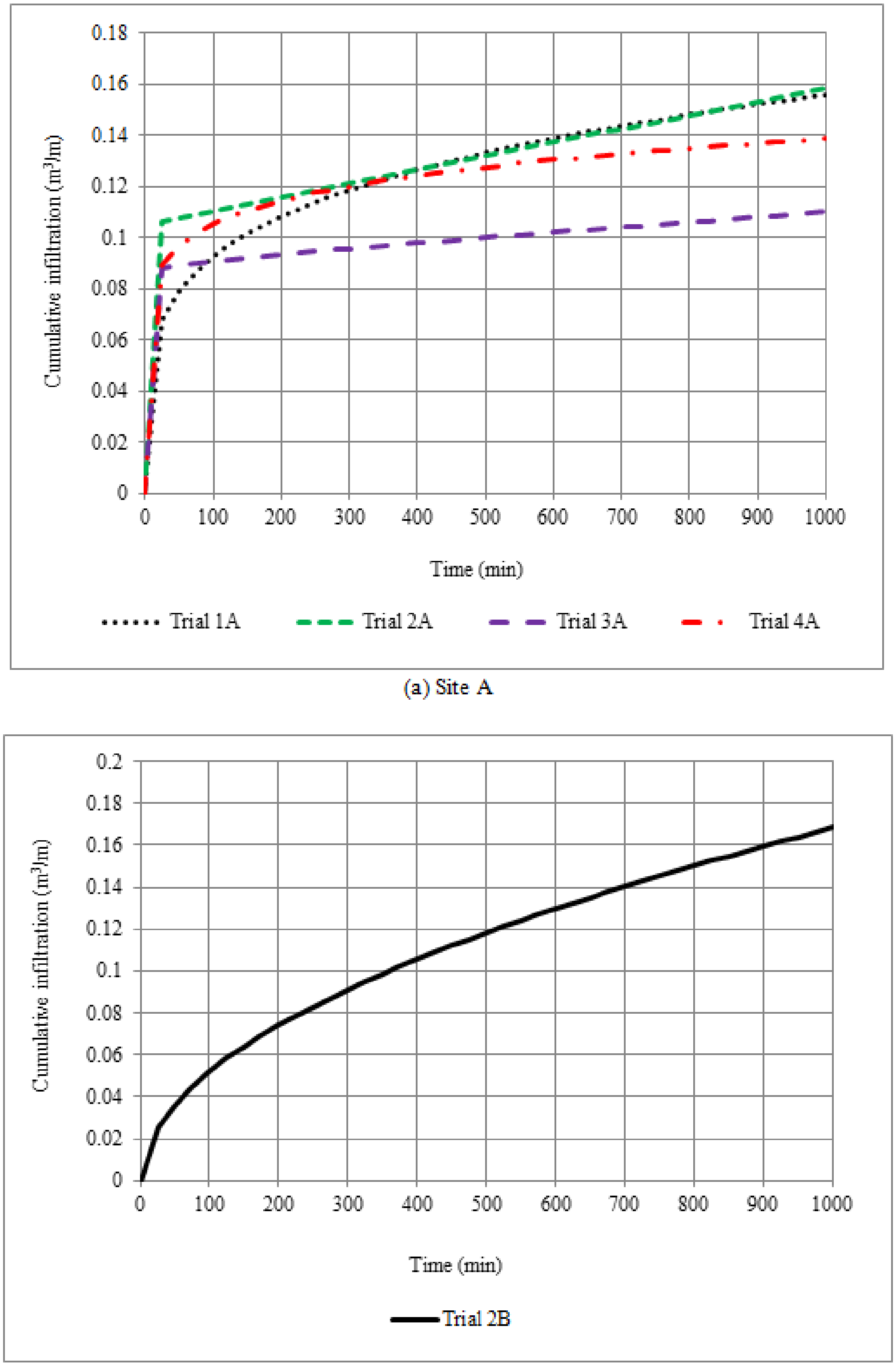
The predicted performance of the five irrigations controlled using the optimisation system is summarised in Table 5.2. The furrow inflows were set by the irrigator, and the target irrigation deficit was also selected in consultation with the irrigator. These performances are based on data collected from the model furrow in which the system control components were placed. The predicted cumulative infiltration performance and advance curves (based on the scaled infiltration characteristics in Table 5.1) are shown in Figures 5.1 and 5.2 respectively (Appendix B.0.9). The optimisation strategy used was to maximise AE while maintaining RE and DU at desired levels shown in Table 5.2.

Table 5.2: Performance as per the optimisation system

	Site A				Site B
Trial number	1A	2A	3A	4A	2B
Time to cut off (min)	424	392	456	584	936
Inflow (l/s)	6	5	3.82	3.3	1.6
Deficit (mm)	80	80	82	90	80
Inflow (incorrect) used to optimise (l/s)	*4.13*	*5.65*	*3.54*	*3.17*	*1.50*
Optimisation strategy					
DU $\geq$	55	95	90	69	30
RE $\geq$	90	95	95	90	85
AE $\geq$	65	57	80	70	58
Predicted Performance (%)					
AE	67	59	81	73	58
AE (with 90% recycling)	67	64	81	73	58
DU	57	95	95	69	30
RE	91	100	99	93	86
Inflow volume (m^3)	105	133	97	111	84
Drainage (%)	32	31	15	27	42
Runoff (%)	0	8.98	0	0	0

However, as mentioned in the introduction to this chapter, an error in the code was discovered after the completion of the above field trials. As a result, the model used the incorrect inflow in the simulation process hence leading to incorrect prediction of: (i) time to cut off, (ii) the predicted performance, (iii) inflow volume, (iv) drainage and (v) runoff (Table 5.2). The inflows that were incorrectly used by AutoFurrow to optimise the irrigations are shown in Table 5.2. Since the model used the correct inflow rates to undertake the scaling procedure, Figures 5.1 and 5.2 represent the correct predicted scaled cumulative infiltration and advance curves respectively.

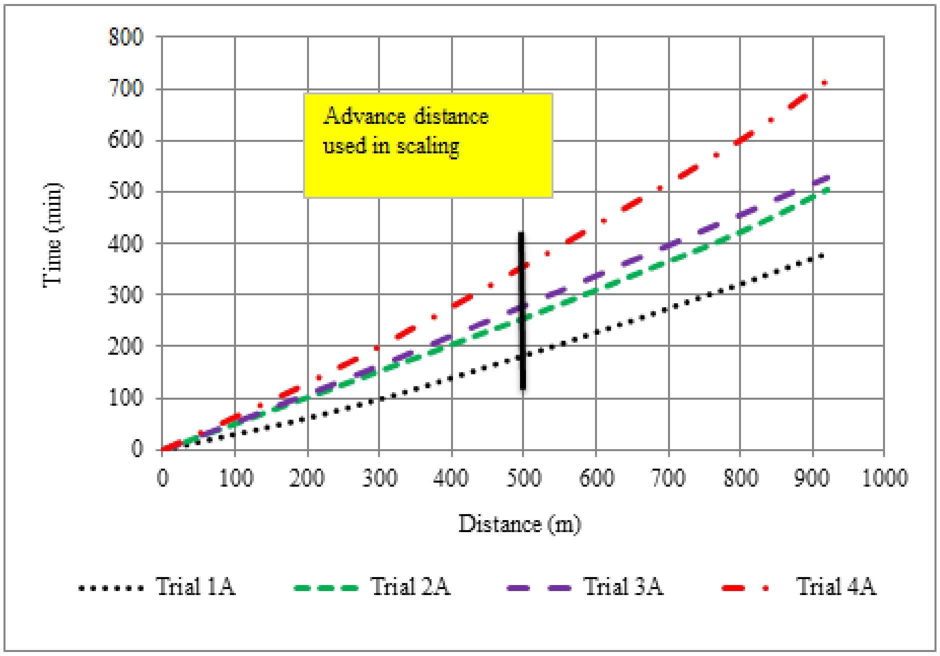
The Kostiakov-Lewis infiltration equation (Eqn. 2.4) was used to plot the cumulative infiltration curves (as were all the cumulative infiltration curves in this dissertation). An example of how this was undertaken is shown in Appendix C.6 (Table C.21). In Figure 5.1 and all subsequent infiltration curves the horizontal axis is infiltration opportunity time, while in Figure 5.2 and all subsequent advance curves the vertical time axis is advance time.



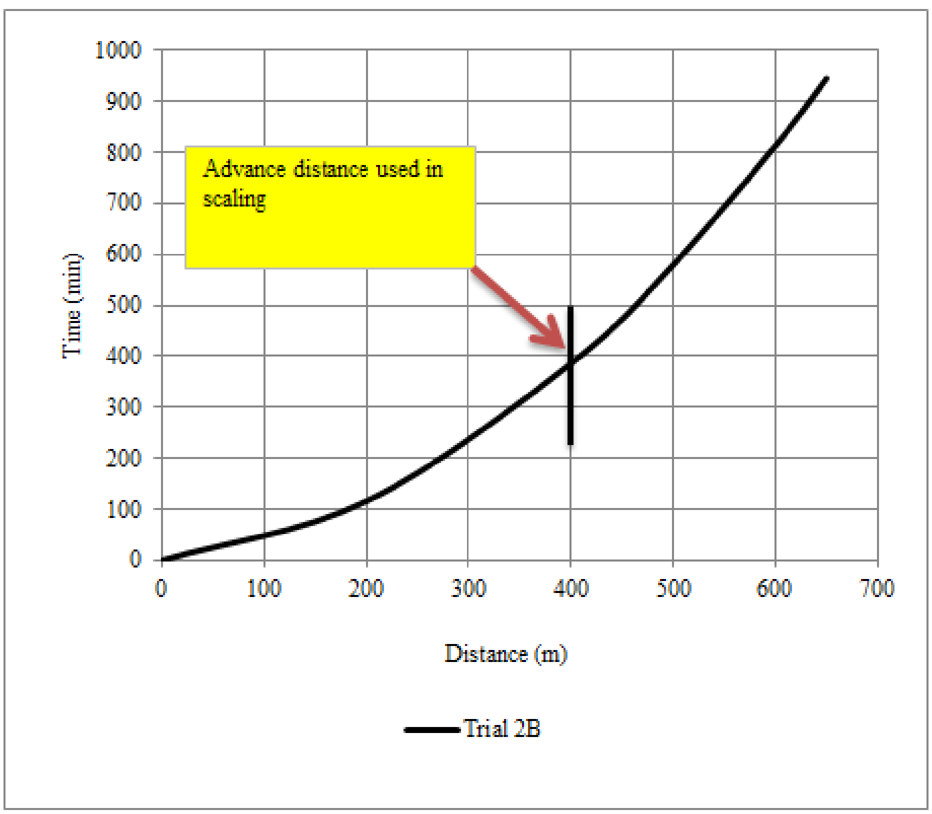
(a) Site A

(b) Site B

Figure 5.1: Predicted (scaled) cumulative infiltration curves



(a) Site A



(b) Site B

Figure 5.2: Predicted advance curves

Table 5.3 shows the predicted performance as per the corrected version of AutoFurrow (that is, the performance that would have been predicted by the optimisation system without the error in the software code). For consistency, the optimisation strategy used in the field was maintained in these new simulations. The predicted times to cut off using this new version of software are lower (except for Trial 3A which remained unchanged) than those obtained during the field trials (which used the earlier version of the software). As already explained, performance shown in Table 5.2 were based on erroneous inflows.

Table 5.3: Predictions of the corrected version of AutoFurrow

	Site A				Site B
Trial number	1A	2A	3A	4A	2B
Time to cut off (min)	280	392	408	568	824
Inflow (l/s)	6	5	3.82	3.3	1.6
Deficit (mm)	80	80	82	90	80
Optimisation strategy					
DU ≥	55	95(93[1])	90	69	30
RE ≥	90	95	95	90	85
AE ≥	65	57	80	70	58
Predicted Performance (%)					
AE	72	66	83	73	62
AE (with 90% recycling)	72	66	83	73	62
DU	67	94	90	73	31
RE	93	100	98	94	85
Inflow volume (m^3)	101	118	94	112	79
Drainage (%)	28	34	15	27	38
Runoff (%)	0	0	0	0	0

[1]No optimum solution found, DU reduced to 93%

5.4 Complete evaluation of the irrigation performance

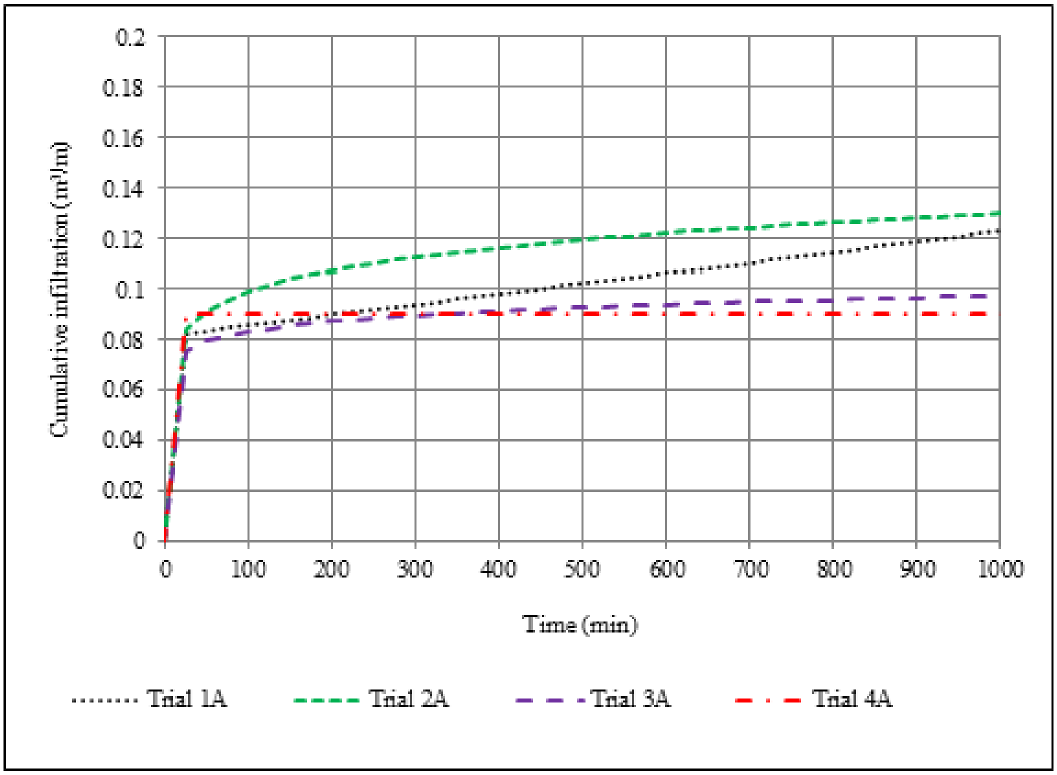
A full evaluation of the irrigation performance (involving flow and advance monitoring) was undertaken for each of the eight trials in the two trial sites. Conventional furrow irrigation evaluations typically use measurements taken from a single (model) furrow which is deemed representative of the entire set of furrows. However since the Irrimate^{TM} advance meters used in the evaluations have eight sensors each, advance data for a similar number of furrows were obtained (Appendix B). This complete set of data was also used to perform simulations for the entire set of irrigation furrows, hereby referred to as multi-furrow evaluation (discussed in the next chapter). The farmer's usual irrigation practice was used to evaluate the performance he would have achieved.

5.4.1 Model furrow evaluation

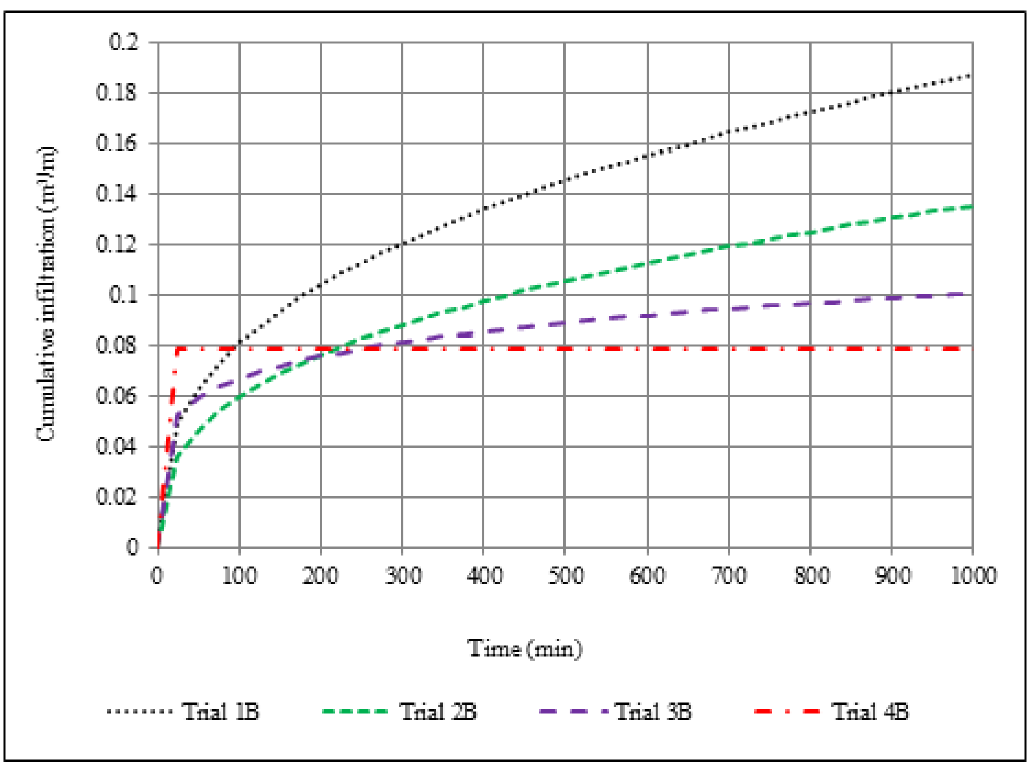
In all cases the complete evaluation process used the same model furrow used in the automated real time optimisation trials. The simulations were undertaken using the SISCO model and the results are shown in Table 5.4. The actual cumulative infiltration curves (derived from the estimated infiltration parameters) and the measured advance curves are shown in Figures 5.3 (and Appendix B.0.9) and 5.4 respectively. The breaks in the measured advance curves (Figure 5.4) were as a result of the slight rain that fell just before the irrigation, thereby false-triggering some advance sensors leading to the omission of the data from the affected sensors.

Table 5.4: Actual irrigation performance

	Site A				Site B			
Trial number	1A	2A	3A	4A	1B	2B	3B	4B
Time to cut off (min)	424	392	456	584	990	936	745	502
Inflow (l/s)	6.00	5.00	3.82	3.30	1.50	1.60	1.54	3.20
Deficit (mm)	80	80	82	90	80	80	80	90
Infiltration parameters								
a	0	1.18E-01	6.80E-02	0	5.11E-01	3.56E-01	1.78E-01	0
k	8.15E-02	5.76E-02	6.09E-02	9.01E-02	4.94E-03	1.16E-02	2.95E-02	7.82E-02
f_o	4.16E-05	0	0	0	0	0	0	1.27E-05
Actual Perf. (%)								
AE	51	65	76	76	57	64	82	63
AE (with 90% recy.)	76	69	87	96	57	68	88	94
DU	98	95	99	100	39	81	90	99
RE	100	100	100	100	89	100	100	94
Inflow vol. (m^3)	153	119	105	116	89	90	69	96
Drainage (%)	12	28	10	0	43	30	10	0
Runoff (%)	37	7	14	24	0	7	8	37

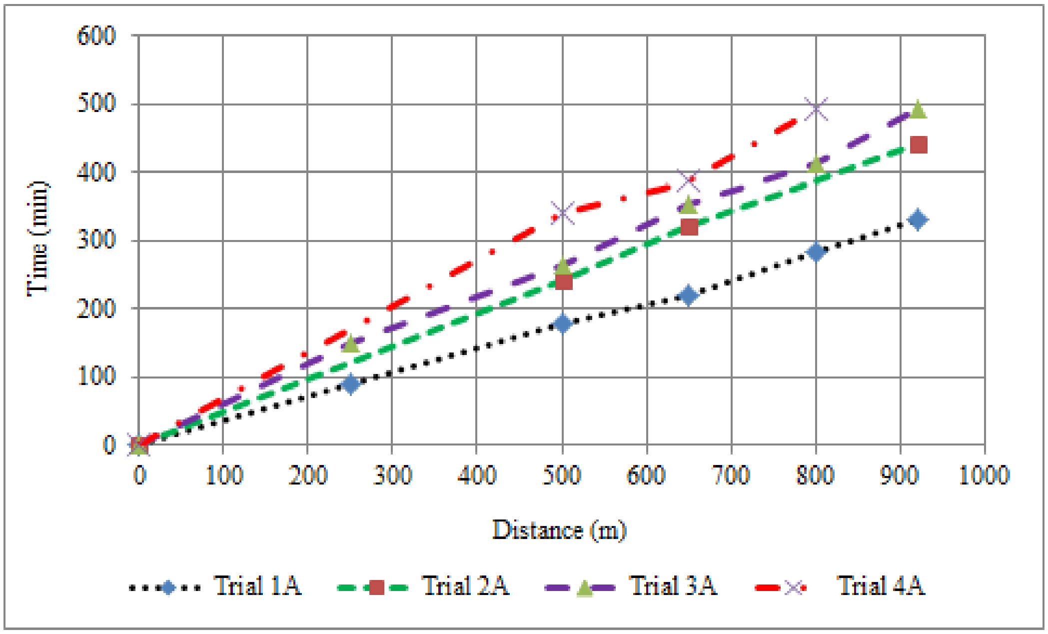


(a) Site A

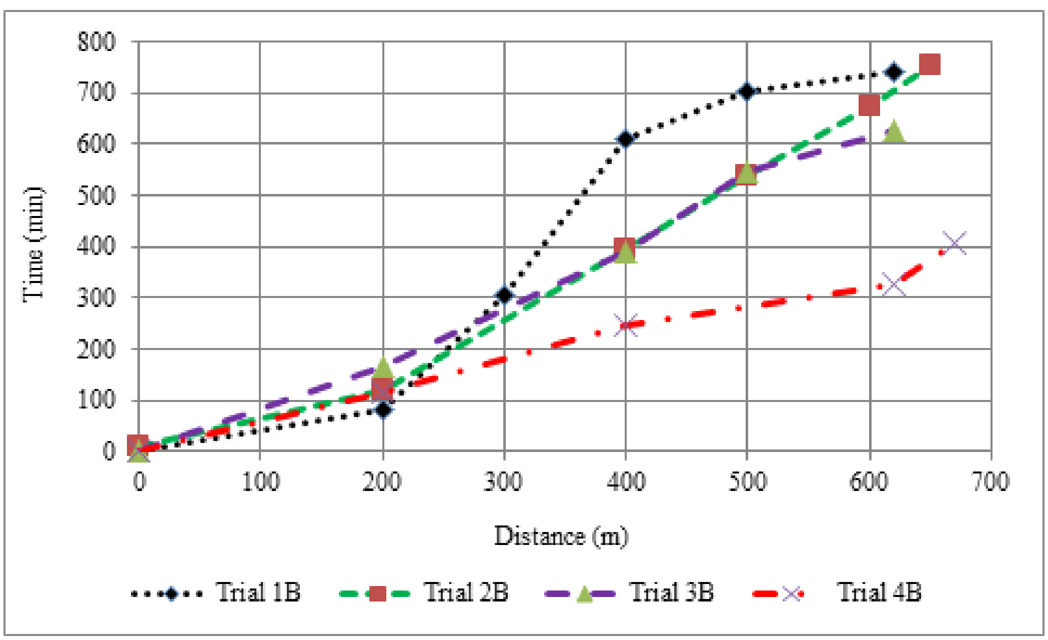


(b) Site B

Figure 5.3: Actual cumulative infiltration curves



(a) Site A



(b) Site B

Figure 5.4: Actual advance curves

5.4.2 Expected performance as per the farmer management practices

The basis of the automated real time optimisation system developed in this study is to optimise the time to cut off in order to improve the irrigation performance. The simulation model however can handle both constant and variable flow. Once the water front reaches the sensor placed approximately midway down the furrow, a signal is relayed to the computer which determines the optimum time to cut off the flow and calculates the expected performance. This time to cut off was used to control the trial set of furrows while the farmer controlled the rest of the furrow sets as per his normal practice. The farmer varied the flow rates throughout the season and hence the time to cut off based on his experiences.

Table 5.5 summarises the performances the irrigator would have been expected to achieve using his own time to cut off. The inflows as well as the irrigation deficit are the same as those used in the automated real-time optimisation system. The infiltration parameters used in the evaluations were obtained from full evaluation of the trial furrow (the same trial or model furrow was used in the optimisation system) during the same irrigation. The data was analysed using the SISCO model.

The table shows that the farmer's times to cut off inflow were higher than what the real-time optimisation and control system would have predicted (Table 5.3), with the exception of Trial 4A. As a consequence, the farmer would have obtained a lower AE and deep drainage losses but higher DU, RE and runoff. In addition the farmer would have applied more water than would have occurred under the automated system. This is consistent with anecdotal evidence which suggest that farmers generally choose to have longer irrigation runs to guarantee that water reaches the end of the field.

It is apparent from Table 5.5 that the farmer was utilising the knowledge gained from preceding irrigations to modify his future irrigations. The farmer progressively reduced the applied volume throughout the irrigation season. It is for this reason that the final irrigation of the season (Trial 4A) had a shorter cut off time than that predicted by the real time control system.

Table 5.5: Performance expected as per farmer time to cut off

	Site A				Site B
Trial number	1A	2A	3A	4A	2B
Farmer's time to cut off (min)	565	489	484	480	936
Inflow (l/s)	6	5	3.82	3.3	1.6
Deficit (mm)	80	80	82	90	80
Infiltration parameters					
a	0	0.11768	0.06781	0	0.35624
k	8.15E-02	0.05763	0.06091	0.09014	0.01157
f_o	4.16E-05	0	0	0	0
Expected performance (%)					
AE	38	53	71	92	64
AE (with 90% recycling)	81	66	86	99	68
DU	100	97	99	100	81
RE	100	100	100	100	100
Inflow volume (m^3)	203	147	112	95	90
Drainage (%)	3	25	9	0	30
Runoff (%)	59	22	20	8	7

The use of the optimisation system thus leads to water savings and lower runoff volumes but at an expense of slightly lower DU, RE and higher deep drainage losses. As explained in the design chapter, the optimisation strategy in the AutoFurrow model is flexible and based on a 'compromise' among the key irrigation performance measures (AE, RE and DU). Optimisation is achieved by specifying in the model input screen the minimum acceptable levels of each of these performance measures. Although runoff water was recirculated by the farmer (leading to higher AE with recycling in Table 5.5), this comes with additional pumping and labour costs. In some instances excessive runoff may also cause soil erosion especially towards the tail-end of the field.

In the system tested in the field only a limited number of functions were automated (advance and inflow measurement), but nonetheless this represents a reduction in labour requirement. The inflow measurement by using a PST was however discontinued due to practical difficulties as has already been explained. Full automation of the water delivery system anticipated in future designs will lead to even more labour savings. The full potential of improvements under real time control system may have been 'masked' by the farmer's apparent use of the trials to improve his irrigation practice throughout the season.

5.5 System hardware and software performance

One of the major aims of the field trials was to test both the hardware and software developed in this study (discussed in Chapter 3). The systems that were tested in the field were: flow measurement, sensing, telemetry and the simulation model. Furrow inflow measurement through inference from pressure measurement using a PST proved challenging as discussed in Chapter 4 of this dissertation. Hence average flow rate measured using ultrasonic flow meter was used in the simulation. Both the sensing (advance sensor) and telemetry systems worked as intended. As mentioned earlier in this chapter, the simulation model (as a result of an error in the code) picked up the wrong inflow in the simulation trials undertaken in the field. The error was caused by the fact that the optimisation process was attempting to use the inflow data from the PST while the scaling process was using the manually entered values. This error was corrected and a new set of simulations performed based on the data collected in the field. The error in the software code notwithstanding, it is concluded that both the hardware and software components of the optimisation system performed well.

5.6 General discussion

It has already been indicated that at Site B, PTB water application method was in use. In addition, Chapter 2 identified some potential factors that might affect uniformity of water application using this method, particularly the possible accelerated flows in some furrows that might be slightly lower in elevation.

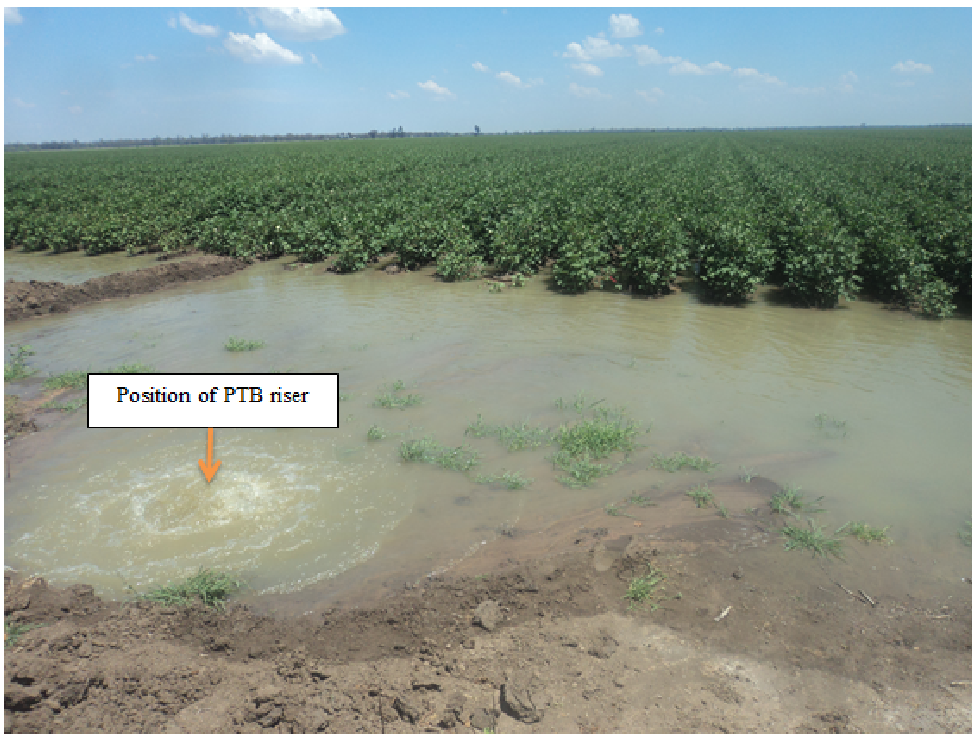


Figure 5.5: PTB water application method

At the trial Site B, each PTB installed was discharging water into 11 furrows. In order to ensure a more uniform distribution of water the PTB was positioned approximately in the centre of these furrows. In the field side the PTB was about 20 cm below the ground level, and water was discharged through a vertical riser fitted to the end of the PTB (Figures 5.5 and 4.4a).

Although it was evident that the design of the system was technically sound, it is virtually impossible to ensure water is evenly distributed into each furrow under this method. Apart from the effect of machinery use that might cause some furrows to be slightly lower in elevation (and possibly wider) thereby leading to accelerated flows (into these furrows), the majority of the surface-irrigated fields are also designed with a small cross slope. This implies that the furrow elevations might be potentially different, and hence accelerated flows into the furrows that are lower in elevation.

The field trials undertaken assumed that water discharged from the PTB riser was distributed uniformly among the 11 furrows. In the next chapter however, simulations will be undertaken to ascertain the effect of this uncertainty of furrow inflow in the prediction of the optimisation system. Nonetheless, the real time optimisation and control system demonstrated potential for water savings (through shorter irrigation times) and labour savings (by automation). This is consistent with previous studies reviewed in Chapter 2 (for example: Latimer & Reddell 1990, Hibbs et al. 1992, Emilio et al. 1997, Dassanayake et al. 2001).

5.7 Conclusion

Initial results from a real-time optimisation and control system for furrow irrigation system have been presented in this chapter. The trials were undertaken at a trial site in St George, and consisted of a total of eight trials out of which five were controlled using the developed system.

As can be expected of any new system, an error was discovered in the code of the software which resulted in the use of incorrect inflow data. Other than that the hardware and software tested in the field performed as expected. Simulations undertaken using the corrected version of the software show that in general the automated real-time optimisation and control system would have led to shorter irrigation times (than that of the farmer) leading to water savings. This inevitably comes with a slight decrease in DU and RE. The system currently is partially automated and the envisaged future complete automation is expected to lead to further labour savings.

The PTB water application method has been shown (in Chapter 2) to be less labour-intensive than the siphon method. However, there is uncertainty over whether the method can ensure uniform furrow inflows. Non-uniformity of furrows inflows has been shown to reduce the irrigation performance.

Chapter 6

Analysis and evaluation of alternative strategies

6.1 Introduction

The results of the preliminary trials conducted to test the optimisation system for furrow irrigation were presented in the previous chapter. The purpose of this chapter is to evaluate the effect of using alternative control and management strategies on the system performance. The parameters investigated are: objective function, flow rate, irrigation deficit, the infiltration scaling process, the model curve, advance distance and multi-furrow evaluation. A sensitivity analysis was also undertaken to investigate the effect of errors in inflow and deficit on the performance and time to cut off predicted by the optimisation system.

6.2 Objective function

The performance predicted by the optimisation system (corrected version) was shown in Table 5.3 while the actual performance as determined by a complete evaluation process was shown in Table 5.4 in Chapter 5. The optimisation strategy employed in the control system trials consisted of the three common measures of irrigation performance - AE, DU and RE. The alternative strategy evaluated in this chapter involved the use of only AE and RE. This is because if RE is set at fairly high level (for example ≥90%) and the maximum AE selected, DU is also likely to be high.

6.2.1 Trial results as predicted by the optimisation system

In order to evaluate the potential improvement in performance of the five field trials controlled by the real-time optimisation system, RE was set at ≥90% and the SISCO model used to determine the best AE achievable (Table 6.1). In all cases only the objective function was varied while the rest of the parameters of the model (infiltration parameters, irrigation deficit and inflow) were kept constant.

Table 6.1: Effect of alternative objective function on the performance of the controlled trials

Trial number	Field performance of optimisation system		Best possible performance of optimisation system	
	AE (%)	TCO (min)	AE (%)	TCO (min)
1A	71.8	280	71.8	280
2A	65.8	392	66.2	360
3A	84.6	408	84.7	376
4A	72.9	568	73.2	536
2B	61.9	824	59.3[1]	904

[1]In the control system field trials RE ≥85% was used for Trial 2B

Table 6.1 shows that with RE $\geq$90% there was little potential for any further improvement in AE. The simulated results for Trial 2B predicted a lower AE than was actually achieved in the field trials. It is worth noting however that in the field trials RE had been set at $\geq$85% for this particular trial.

6.2.2 Trial results based on the full measured data (actual infiltration)

As already explained in Chapters 4 and 5, a full evaluation of the irrigation performance was undertaken for each of the eight field trials. This has been referred to as the 'actual irrigation' since unlike the control system, it was not based on the scaling procedure but the actual measured infiltration. Both the optimisation system trials and the actual irrigation performances were based on the same trial or model furrow.

The procedure used to assess the potential improvement achievable in the actual irrigations through varying the objective function was exactly the same as in the subsection above. The results of these evaluations including the predicted time to cut off (TCO) are shown in Table 6.2.

Table 6.2: Effect of alternative objective function on the performance of actual irrigation

Trial number	Actual irrigation (using actual infiltration)		Best possible performance using actual infiltration	
	AE (%)	TCO (min)	AE (%)	TCO (min)
1A	50.8	424	99.1	190
2A	65.2	392	71.6	328
3A	76.1	456	90.9	352
4A	75.5	584	100	406
2B	63.6	936	76.7	694

Contrary to the simulation results for the control system (Table 6.1), this analysis suggests that up to 48% increase in AE could have been achieved if the actual infiltration was predicted perfectly (as will be shown later). The alternative objective function also predicted a lower TCO for all trials.

6.2.3 Implications on the optimisation system

The selection of the objective function used in the field trials aimed to achieve the best possible AE while maintaining RE and DU at some desired levels. The software developed (AutoFurrow) is designed to display an error message whenever the selected strategy is unachievable. This therefore provides an opportunity to revise the strategy and quickly re-simulate the irrigation. This process thus provides a good indication of what optimisation strategies are feasible, and may explain why the use of alternative objective function suggests no further scope for improvement in AE (Table 6.1).

It has been shown in Chapter 5 that the optimisation system gave better performance than the grower achieved. This confirms that this research has achieved one of its core objectives of improving the performance of the furrow system as indicated in Chapter 1. However, on average, Tables 6.1 and 6.2 show that the actual irrigation performance was slightly less than that predicted by the real-time optimisation system. Perhaps most significantly, both the actual irrigation performance and that predicted by the real-time optimisation system were much less than that suggested by the post-irrigation optimisation of the actual irrigation which utilised the actual infiltration (Table 6.2). This indicates that there is a potential to significantly improve the performance of the new system.

The above results also suggest that a simpler objective function that maximises AE while ensuring that the RE was maintained at a desired value may provide a similar result to that which relies on a combination of the three performance measures (AE, RE and DU). The advantage of using a simpler objective function is that it has the potential to improve the robustness of the optimisation system because less computations are required.

The rest of this chapter is dedicated to investigating other potential factors contributing to the performance of the control system (flow rate, model infiltration curve and the infiltration scaling process). This will be achieved by evaluating alternative strategies through a series of simulations using the SISCO model.

6.3 Flow rate

In the field trials conducted to test the automated optimisation system, the flow rate was kept constant. The complete evaluation undertaken (actual irrigation performance) also relied on the same constant flow rates. In this chapter, evaluations were undertaken to investigate the effect on AE, RE and TCO of using different flow rates for both the controlled field trials and the subsequent complete evaluations.

6.3.1 Constant TCO

In the first case, in the SISCO model, flow rate (Q) for each trial was varied from between -75 to +100% while all the other parameters (including the TCO) were kept constant. The results of these simulations for Site A are plotted in Figures 6.1 and 6.2 (complete results shown in Appendix C).

The simulations undertaken for the optimisation system trials suggest that a reduction in inflow has minimum effect on AE, while an increase in inflow leads to a decrease in the AE predicted (Figure 6.1). The corresponding simulations based on the actual infiltration data (Figure 6.2) suggest that there are gains in AE with a decrease in inflow. Trial 1A for instance suggested an increase in AE of 48% with a 75% reduction in inflow. An increase in inflow also suggested a decrease in AE. The respective plots of varied flow versus RE (Figures 6.3 and 6.4, and Appendix C) and their patterns are opposite to the first two graphs.

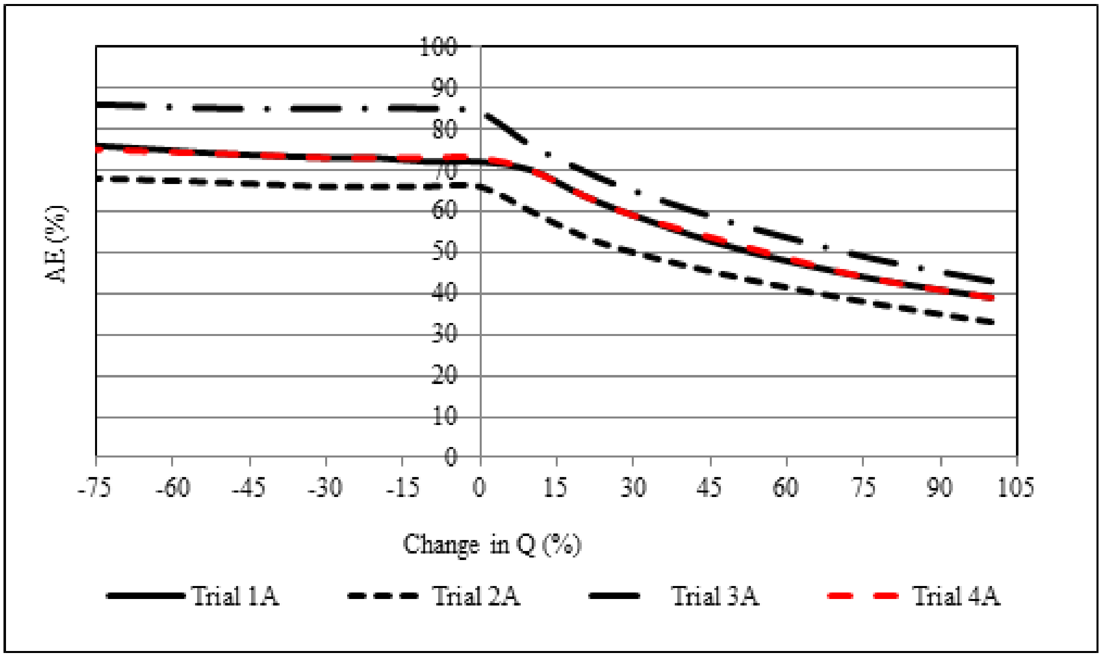


Figure 6.1: Effect of varying Q on AE (scaled infiltration)

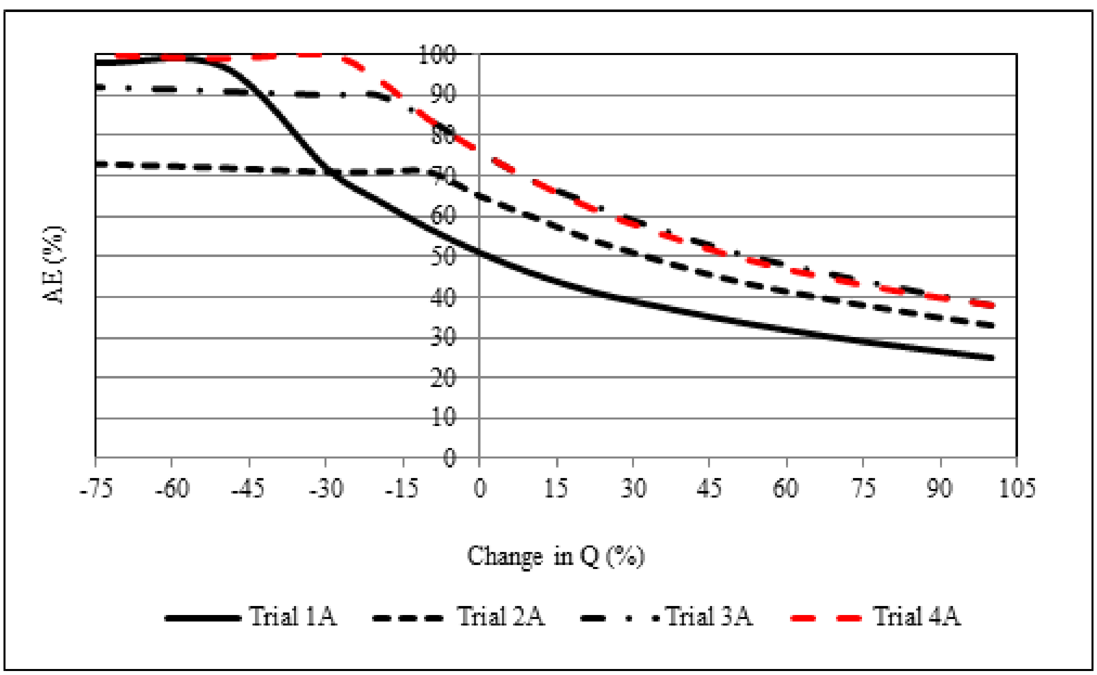


Figure 6.2: Effect of varying Q on AE (Actual infiltration)

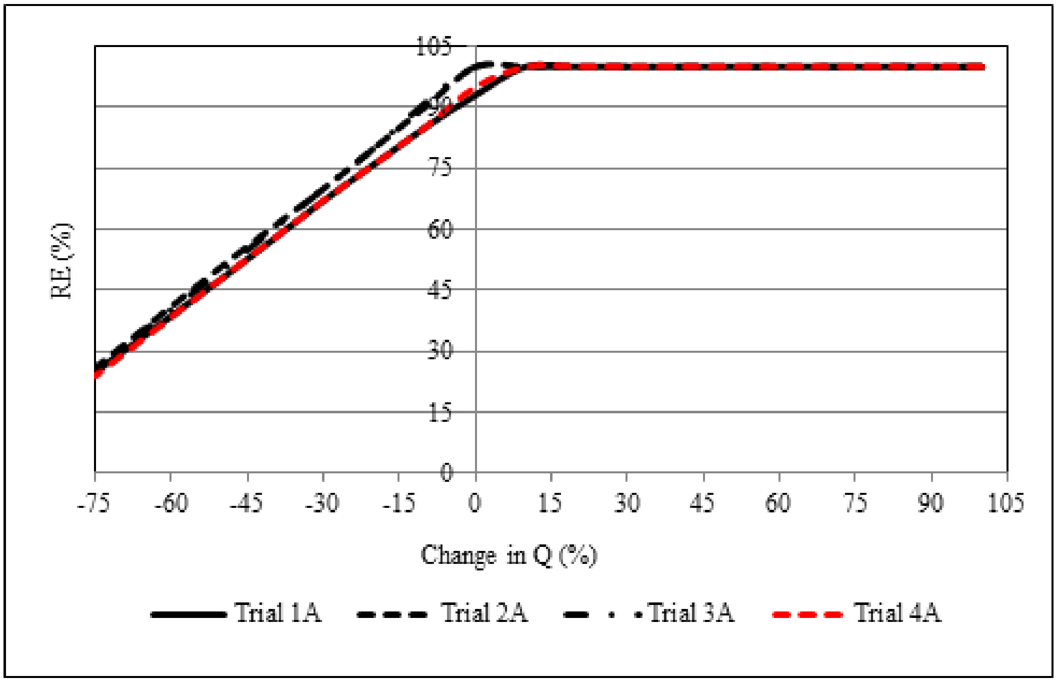


Figure 6.3: Effect of varying Q on RE (scaled infiltration)

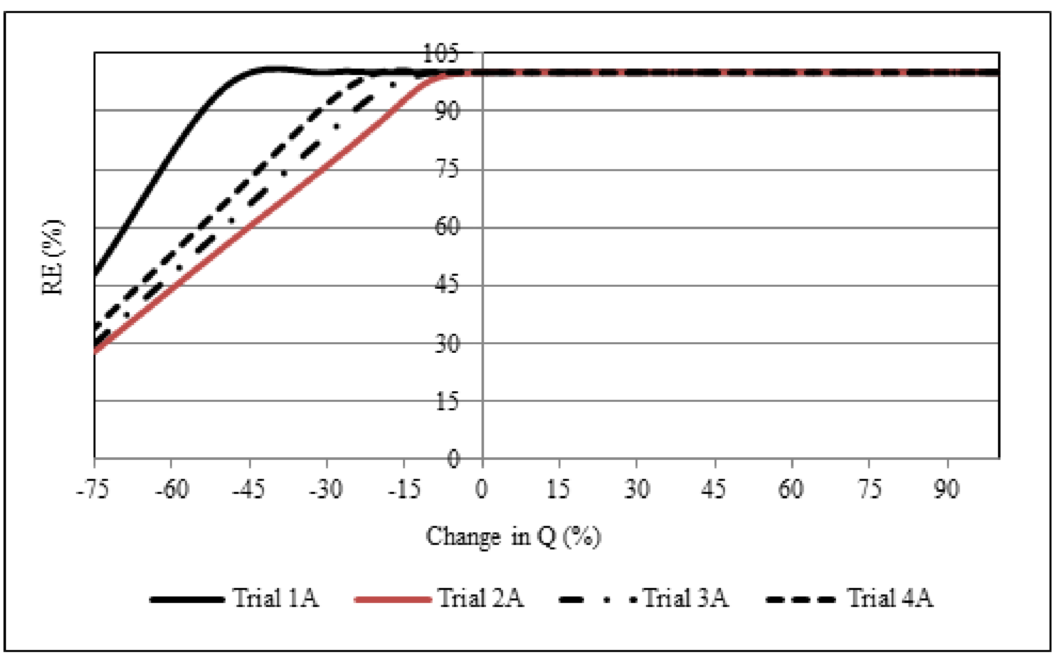


Figure 6.4: Effect of varying Q on RE (actual infiltration)

Figures 6.1 - 6.4 show that there are potential gains in AE in reducing flow rate; however the RE may fall to undesired levels (which may include water not reaching the end of the field). The figures suggest an optimum flow rate for this site of about 3 l/s. Figure 6.5 is a plot of AE and RE versus change in Q for Trial 1A conducted to test the optimisation system (see also Appendix C).

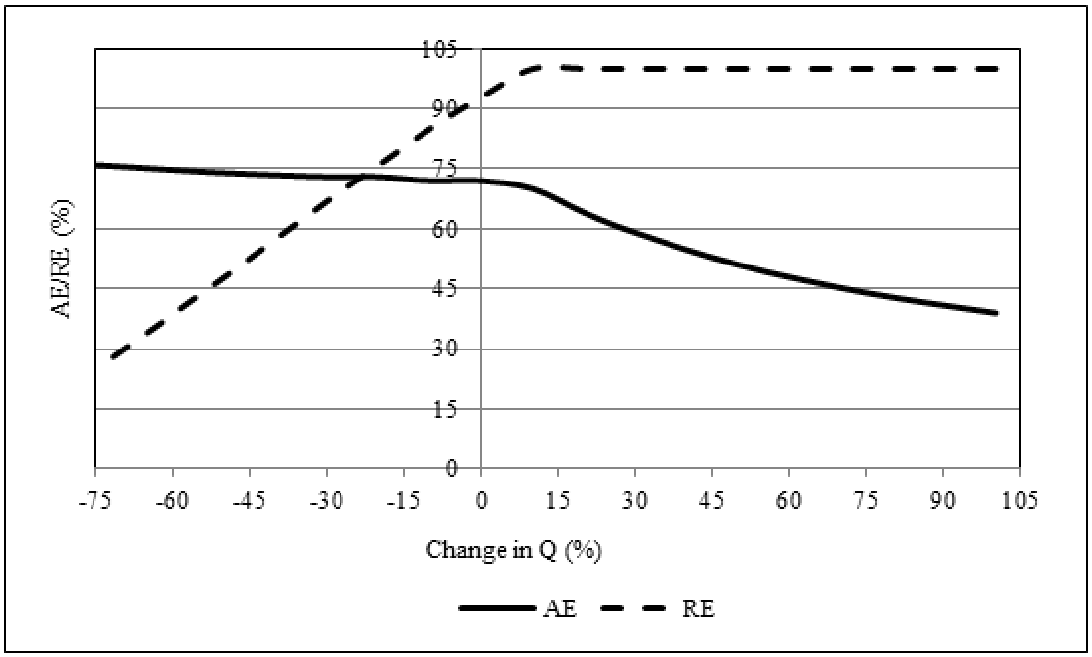


Figure 6.5: Optimum Q for maximum AE and RE (optimisation system - Trial 1A)

6.3.2 Variable TCO

As already indicated, the above simulations were undertaken with a constant TCO. New simulations were undertaken to investigate the effect of varied flow on both AE and TCO with RE of ≥90% (Table C.6, Appendix C) for the data obtained from the optimisation trials. These are plotted in Figures 6.6 and 6.7 (and Appendix C). In effect, this procedure serves to test the sensitivity of flow rate in the optimisation system. This is particularly important for the trials undertaken using the PTB system since apparent uncertainty exists in inflows (as discussed in Chapter 5).

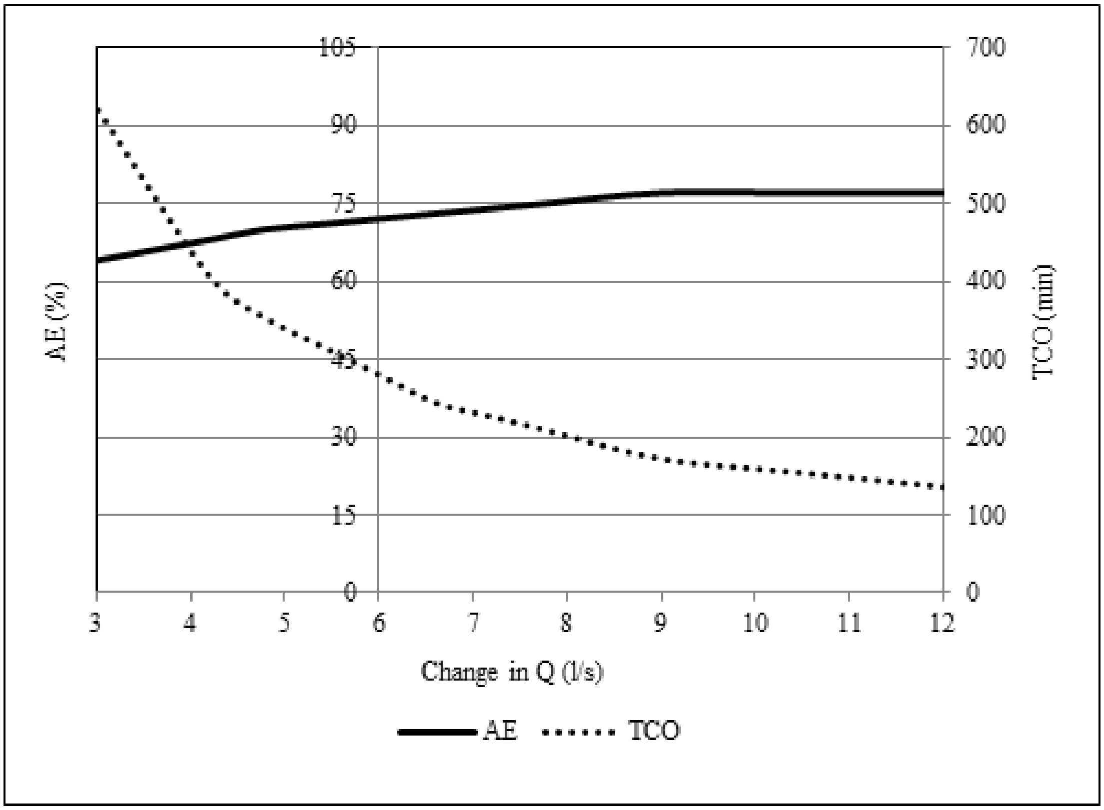


Figure 6.6: Effect of varying flow on AE and TCO (scaled infiltration - Trial 1A)

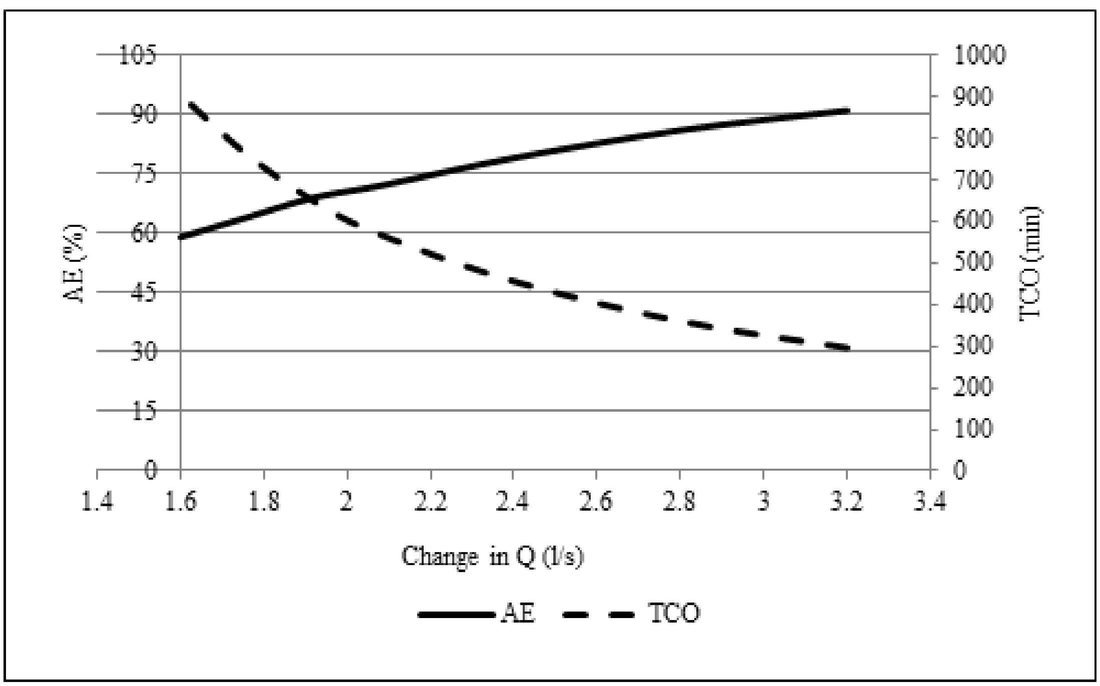


Figure 6.7: Effect of varied flow on AE and TCO (scaled infiltration - Trial 2B)

The plots show that for all trials in Site A, a decrease in Q leads to a rapid increase in TCO and a slight reduction in the predicted AE. The opposite is exhibited by an increase in Q. In terms of improving the AE, the evaluations conducted on data collected from Site A seem to suggest that any change in Q has minimal effect and therefore relatively unimportant. It would appear that the flow rates used by the irrigator at this site were about optimum. On the contrary, a study undertaken by Gillies et al. (2010) in the bay irrigation systems within the Goulburn Murray Irrigation District (GMID) concluded that higher flow rates offer potential gains in irrigation efficiency. However this site (GMID) appeared to have an unusual infiltration characteristic and hence these results would not necessarily translate to other sites.

As already stated, the inflow for Site B was relatively low at only 1.6 l/s. Evaluations undertaken here (Figure 6.7) show that any reduction in inflow leads to RE falling below the threshold of $\geq$90%. While the decrease in TCO with an increase in Q is comparable to evaluations conducted on Site A, the corresponding increase in AE is more rapid. The fact that an increase in Q leads to a significant increase in AE seems to confirm that the inflow used in this field trial may have been too low.

6.4 Irrigation deficit

The significance and methods commonly used to estimate soil moisture deficit have been covered in section 2.6 (Chapter 2). As explained in Chapter 4, the target deficit irrigation was decided upon by the farmer on whose property the optimisation trials undertaken in St George. This section of the dissertation presents the evaluations carried out to test the sensitivity to the soil moisture deficit used in the AutoFurrow software.

Irrigation deficit was varied by between -50 and 50% of the actual value and the SISCO model used to run simulations. The model curves used in the actual field trials and flow rates were maintained but RE was set at $\geq$90%. In essence the only variable changed in the SISCO model main input screen was the irrigation deficit. The effect of this on AE and TCO are shown in Figures 6.8 and 6.9 (and C.2 - Appendix C).

The results suggest that within the limits tested and with the exception of Trial 2B, varying the irrigation deficit has minimal effect on the predicted TCO. In all trials increasing the deficit meant an increase in the predicted AE. The exceptional behaviour of the TCO versus change in irrigation deficit in the case of Trial 2B may be as a result of the very low rates used.

These results (based on RE of $\geq$90%), imply that the TCO predicted by the automated system is not very sensitive to the irrigation deficit, and even an error of up to 50% in its measurement or estimation may not significantly affect the predicted TCO. However, any change in the deficit leads to a change in the predicted AE. Thus these findings confirm that measurement or estimation of irrigation deficit has an impact on surface irrigation evaluations, an observation that was made in section 2.6 (Chapter 2).

An investigation was also undertaken to determine the effect of varying the irrigation deficit on AE and RE if the TCO is kept constant (Figures 6.10 and 6.11, and Appendix C). The plots suggest that a decrease in irrigation deficit has almost no impact on the predicted RE. This trend is maintained as the deficit is increased by about 20%. Beyond this the RE reduces slightly. On the other hand the predicted AE increases with an increase in the irrigation deficit. The minimum effect of varying the irrigation deficit on RE further confirms the observations made above that the TCO used in the optimisation system is not very sensitive to the irrigation deficit.

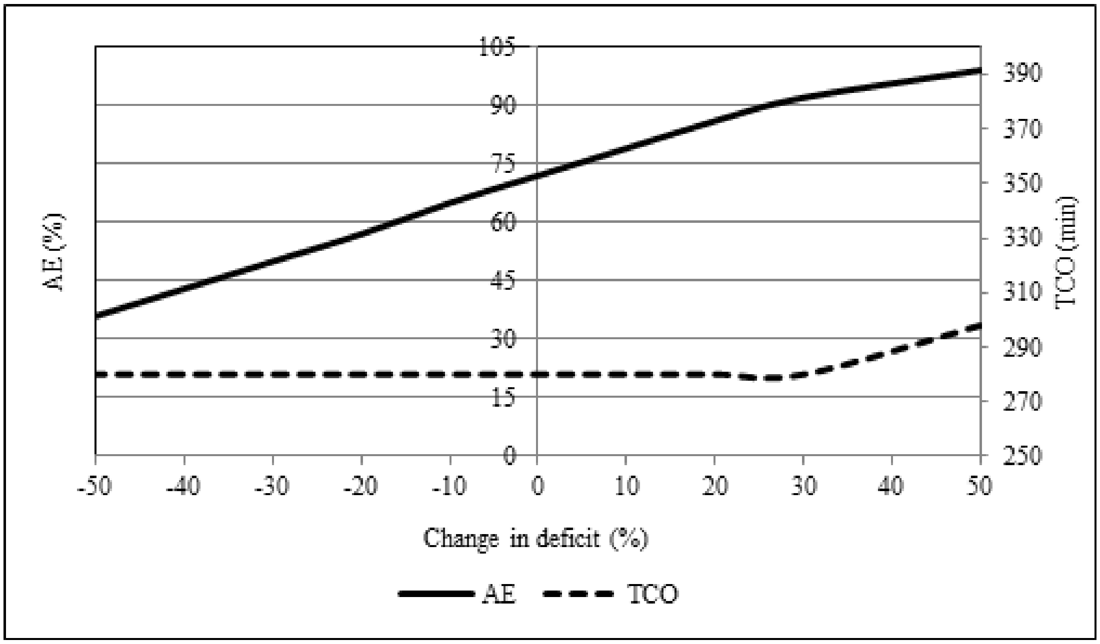


Figure 6.8: Effect of varying deficit on AE and TCO (optimisation system - Trial 1A)

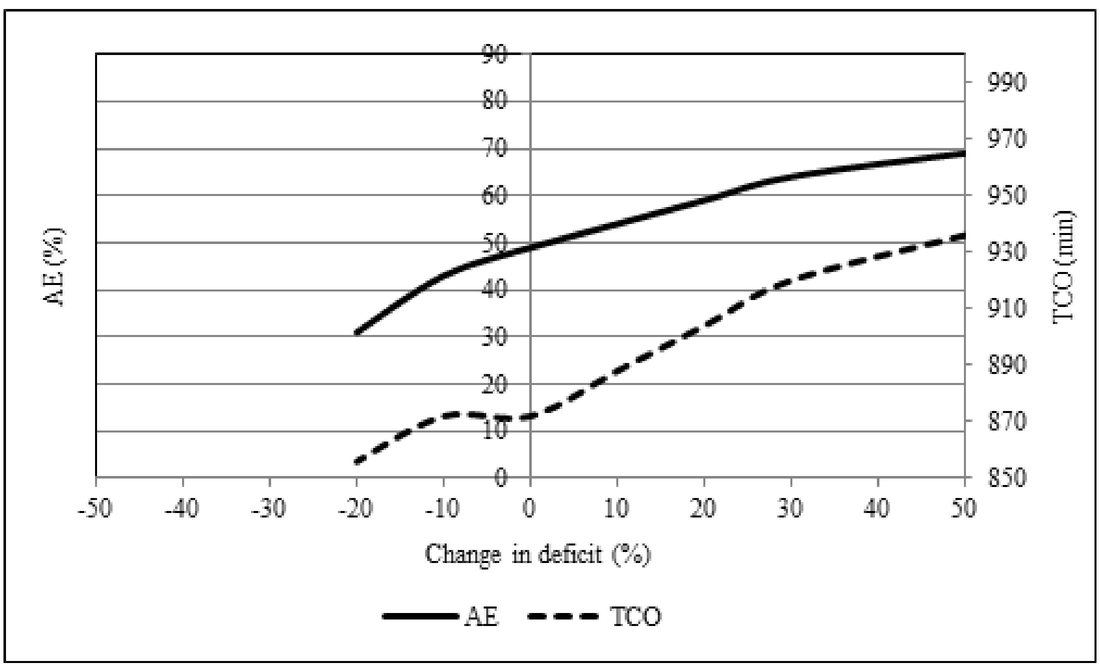


Figure 6.9: Effect of varying deficit on AE and TCO (optimisation system - Trial 2B)

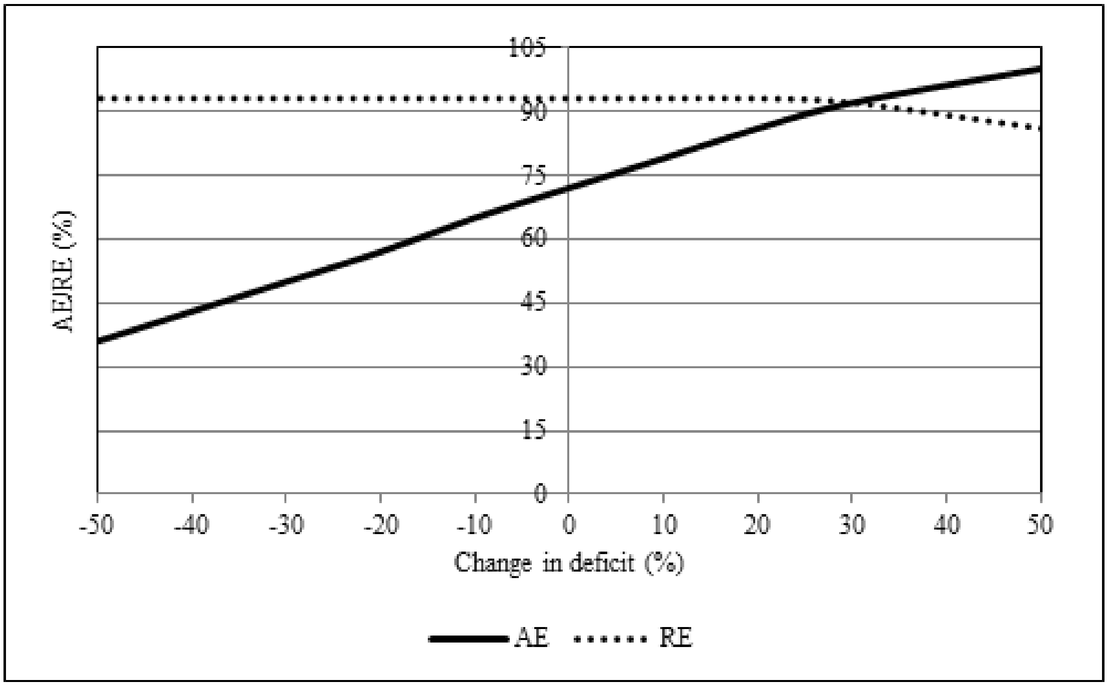


Figure 6.10: Effect of varying deficit on AE and RE (optimisation system - Trial 1A)

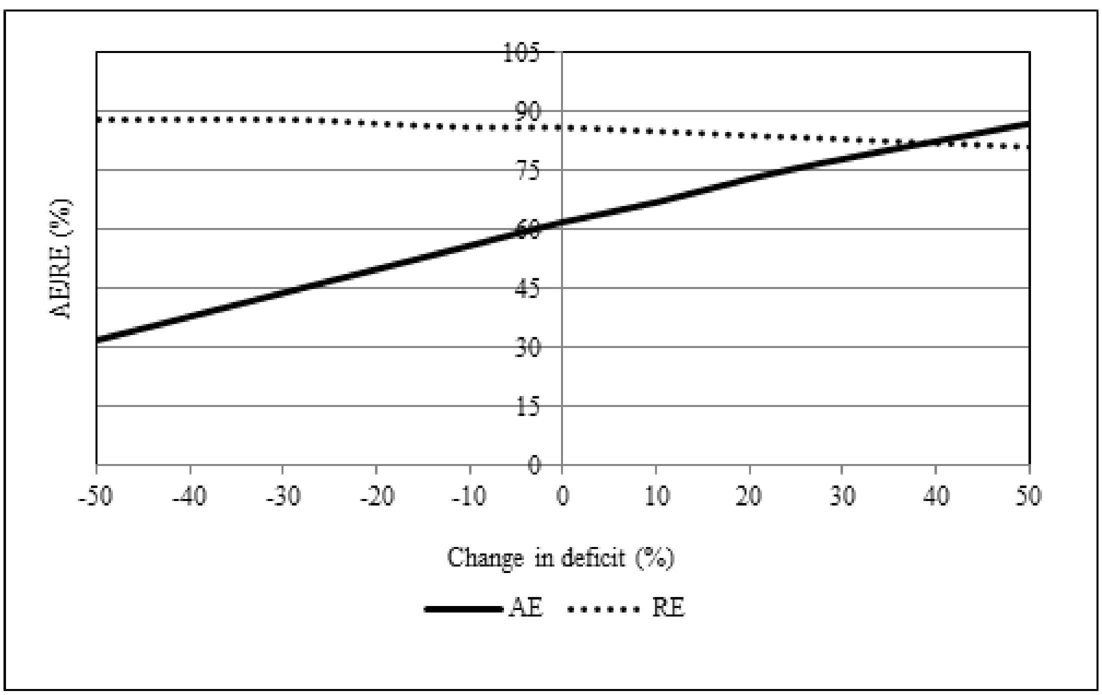


Figure 6.11: Effect of varying deficit on AE and RE (optimisation system - Trial 2B)

Finally, it seems reasonable to conclude that any reasonably accurate method of estimation of the irrigation deficit can be used in the optimisation system. The insensitivity of the TCO to the irrigation deficit does not justify the use of expensive or time-consuming methods to determine the irrigation deficit. This is because in the optimisation system the TCO is the only management variable that is manipulated to achieve the desired performance.

6.5 Infiltration scaling process

The objective of scaling the infiltration is to be able use a minimum amount of data to infer the infiltration characteristics of a set of furrows while the irrigation is underway. These inferred or scaled infiltration parameters are then used to optimise the same irrigation event, which is the essence of real-time optimisation and control of furrow irrigation. The scaling procedure has already been discussed in detail in Chapter 3 and two approaches have been identified:

- Using a model infiltration curve to formulate a scaling factor (F) based on the volume balance model (as used by Elliot & Walker 1982) and the use of only one advance point (Khatri & Smith 2006); and
- Calculating the scaling factor using the full hydrodynamic model and the use of one more advance points (Gillies et al. 2010). This has been incorporated into the SISCO model.

The software developed in this project uses the former approach and hence did the analysis presented in Chapter 5 (section 5.2). This method was used by Khatri & Smith (2006) to evaluate data from 44 furrow irrigation events from two different fields, and the scaled infiltration curves were found to be similar in shape to corresponding curves produced using the full set of advance data.

In the field trials undertaken in St George, a total of eight furrows were monitored but one representative furrow was picked and used as a model furrow. The hardware items described in Chapter 3 were deployed in this furrow for the purpose of performing real-time optimisation and control. Therefore the advance time to the point where the advance meter was placed along this furrow (approximately midway) and other inputs (including the model infiltration curve) were used in the scaling procedure to predict the infiltration characteristics of the set of furrows and hence optimise the irrigation and determine the optimum time to cut off flow. Also, as explained earlier in Chapter 3 a full evaluation was undertaken using the full set of advance data obtained from the multiple 8 m - wide advance sensors placed across the furrows (Chapter 4).

In order to assess the effectiveness of the scaling procedure employed in the real time optimisation trials, the model, actual and scaled cumulative infiltration curves were plotted in the same graphs as shown in Figures 6.12 and 6.13 (and Appendix C). Included in these graphs are cumulative infiltration curves obtained by using the SISCO model to perform the scaling process (SISCO scaled).

It is clear from these graphs that for some of the trials there are some differences between the shape of the scaled and the actual cumulative infiltration curves. This implies that in these cases the scaling procedure has not accurately predicted the infiltration characteristics. This will obviously have some impact on the irrigation performance predicted and hence the recommended time to cut off. This has also reduced the scope for performance improvement in the case of the trials conducted to test the optimisation system (Table 6.1). Overall the scaled cumulative infiltration curves produced using the SISCO model were closer to the actual curves than those generated using the optimisation software (which is based on the volume balance model).

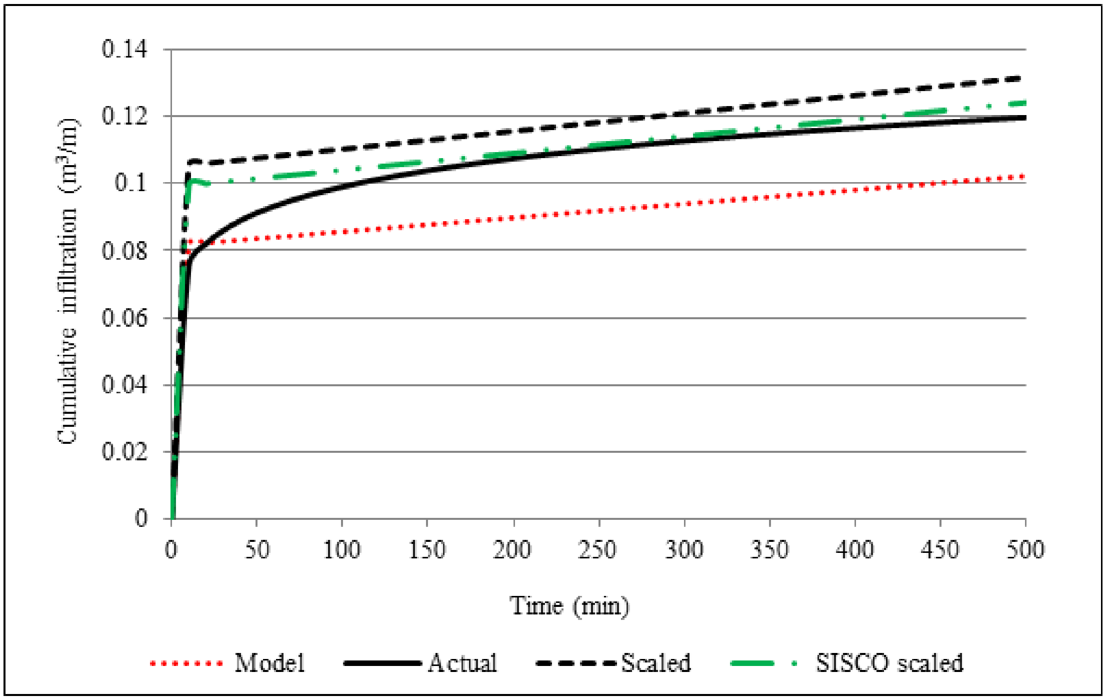


Figure 6.12: Model, actual and scaled infiltration curves (Trial 2A)

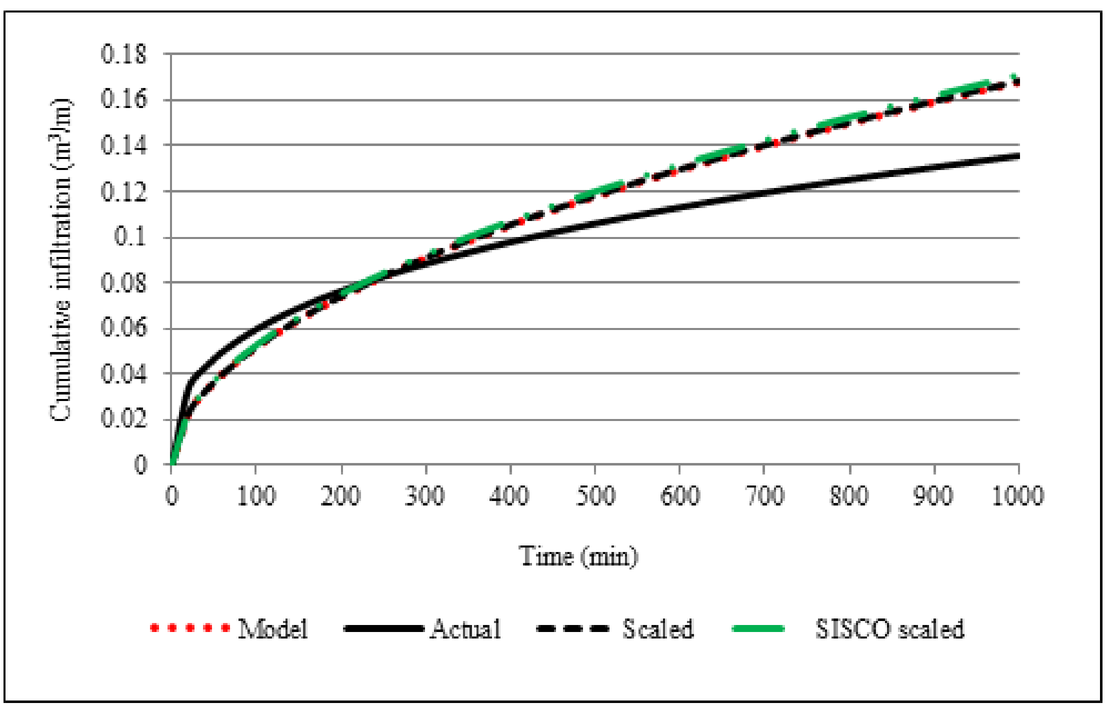


Figure 6.13: Model, actual and scaled infiltration curves (Trial 2B)

The minor difference between the full hydrodynamic and volume balance scaling may be as a result of the use of arbitrary factors such as r and σ_y in the latter model. As indicated in Subsection 3.3.5, σ_y (the surface shape factor) is traditionally assumed to be constant (0.77). The advance curve parameter r used in AutoFurrow was estimated using the IPARM model (Figure 4.12). On the other hand, the difference between the predicted and actual cumulative infiltration curves may have been caused by inaccuracies in the measurement of the advance curves (more discussion in the next section) or the selection of the model infiltration curves. The latter will be pursued further in this chapter. In addition, the effect of the advance distance on the infiltration scaling process will be investigated.

6.6 Comparison of advance curves

To evaluate the accuracy of the scaling method employed in AutoFurrow, the scaled infiltration parameters were used in the SISCO model to predict the advance curves for each of the five irrigations controlled using the optimisation system. These were then compared with advance curves produced from the actual (measured) advance data and those produced by the SISCO model using the actual infiltration. The three advance curves are indicated as ‘Pre’, ‘Act’ and ‘Act infil’ respectively in Figures 6.14 and 6.15 (and Appendix C.4).

Although the curves generally seem to be similar, the scaling procedure predicted a slightly slower advance in all the trials. The points of divergence seem to be around the position where the advance sensor was placed (500 and 400 m for Site A and Site B respectively). The likely reasons for these differences are the shape of the model infiltration curve and possibly the variation of the infiltration characteristics of the soil between the two halves of the field. The possible variation of infiltration characteristics could have been occasioned by long furrows (970 m for Site A). In this case the problem can probably be solved by using different

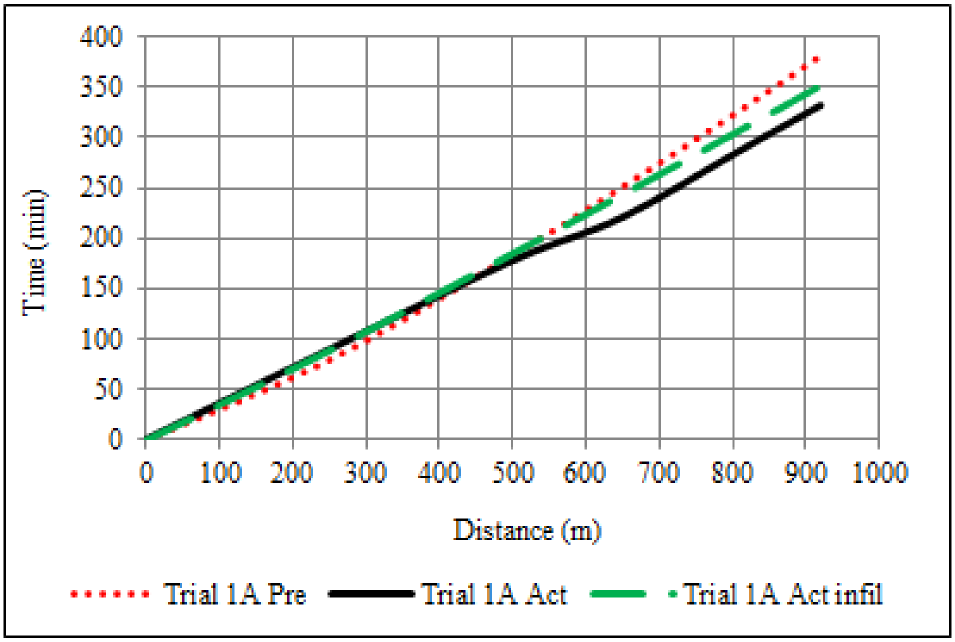


Figure 6.14: Predicted and actual advance curves - Trial 1A

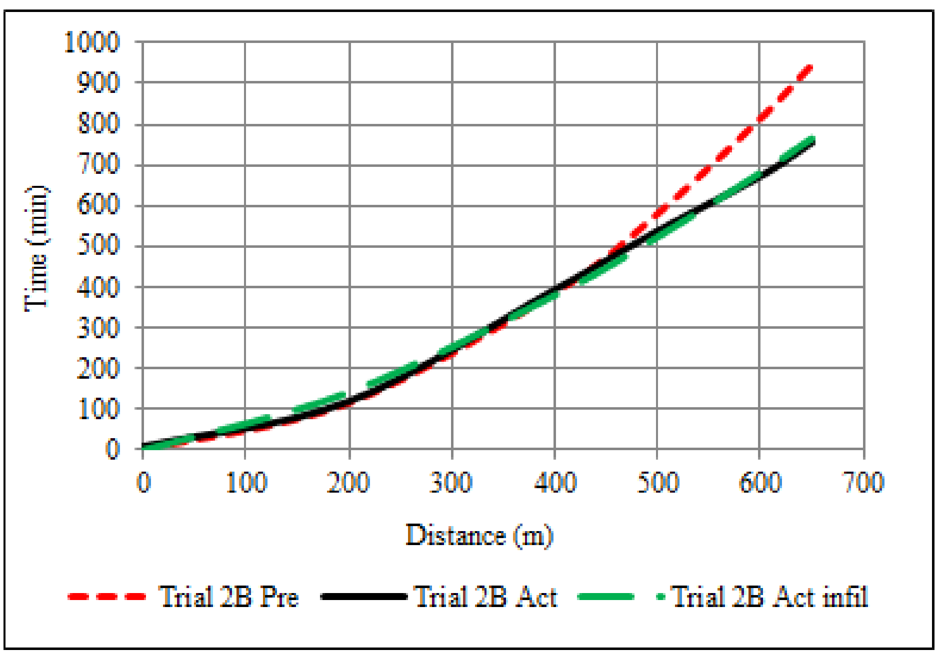


Figure 6.15: Predicted and actual advance curves - Trial 2B

infiltration functions for the two halves of the field. The assumptions inherent in the volume balance model are another possible cause of the difference between the actual and the scaled advance curves (use of arbitrary r and σ_y parameters as noted above).

There were also minor differences in shape between the advance curves plotted from the actual measured data and those that were produced by the SISCO model using the actual infiltration (especially in the case of Trial 1A - from the midway point and onwards). A close scrutiny of the actual advance curve of Trial 1A reveals a small depression at about 600 m mark. This may have been caused by a delay by the Irrimate^{TM} advance sensors in registering the arrival of the water front. This may be caused by a variety of reasons such as the sensor being lifted above the water level by trash in the furrows.

As a result of the slight under-prediction of advance rates, the predicted cumulative infiltration curves lie slightly higher than the actual cumulative infiltration curves as determined through a complete evaluation as demonstrated in the above subsection. The performance of the optimisation system is thus limited by the inaccuracy in predicting the soil infiltration rates (as observed in Section 6.2).

6.7 Selection of the advance distance

6.7.1 Introduction

As already indicated in Chapter 5, an advance point of approximately midway (500 and 400 m for Sites A and B respectively) was selected as the distance to be used in the scaling process. This is where the advance meter used in the optimisation trials was placed. The choice of the advance distance was informed by past studies for example Langat et al. (2008), who concluded that the use of the midpoint is a reasonable compromise, that is, the predicted infiltration parameters are sufficiently accurate and it allows enough time to evaluate and eventually implement the desired decisions (e.g. the time to cut off).

Using data collected during the five irrigations controlled using the optimisation system (presented in Chapter 5), an investigation was undertaken to determine the effect of the advance distance on the scaling factors, cumulative infiltration and the predicted advance curves. An analysis was also conducted to quantify the effect of the advance distance on the irrigation performance of the optimisation system including the predicted time to cut off. These evaluations involved a series of simulations using the SISCO model.

6.7.2 Effect of advance distance on scaling factor and cumulative infiltration

To determine how the scaling factor might be affected by the choice of the advance distance selected for use in the optimisation system, scaling factors were calculated at various points along the length of the furrows. The points where the Irrimate^{TM} advance meters were located were chosen for this purpose because the actual (or measured) advance times were required for scaling (that is advance times to these points were available - Appendix B).

A simple Excel program based on the scaling equation (Eqn. 3.4) was formulated to calculate the scaling factors as well as the scaled infiltration parameters at these various points. This procedure is illustrated in Table 6.3 for Trial 1A (and the rest of the results in Appendix C.5). The results for all the trials (both sites) are summarised in Table 6.4 and plotted in Figures 6.16 (Site A) and 6.17 (Site B) for ease of visualisation of any trends that may be present.

For Site A, as was observed in Chapter 5, scaling factors for Trial 1A are distinctively higher than those obtained for the rest of the trials; the most probable reason being the model infiltration curve used. Each trial in this site however follows the same trend - general decrease in scaling factors with the increase in the distance along the length of the furrow. For Site B, a similar trend is evident for advance distances beyond 400 m. However, as observed by Khatri & Smith (2006) and Langat et al. (2008), the scaling factors tended to converge to a constant value (Subsection 3.4.3).

In Subsection 3.3.5, the scaling factor has been defined as the ratio between infiltrated volume as calculated by the volume balance model in the trial furrow and the infiltrated volume as calculated by the parameters of the model infiltration curve. In the present analysis, the advance distance used in calculating infiltrated volume is varied, but the same model curve is used. Hence, it follows that the change in scaling factor is caused by the change in the estimated infiltrated volume in the model furrow. And since the scaling factors have generally reduced with the increase in advance distance, it can be concluded that the infiltrated volume in the model furrow was predicted to reduce with advance distance. Since the flow rate did not change, the variability in scaling factor can be as a result of variability in soil infiltration characteristics along the furrow or an artefact of the method used to estimate infiltrated volume in the model furrow (scaling technique).

Another possibility is the error in the prediction of the surface storage. Early in the irrigation the surface storage is a large component of the water balance, therefore any errors will have large consequences for the estimated infiltration. As time progresses, the surface storage becomes a smaller part of the water balance and therefore the estimated infiltration becomes less sensitive to it.

Table 6.3: Effect of advance distance on scaling the factor - Trial 1A

Trial 1A model curve values					
a	0.2264				
k	0.01329				
f_o	0				
r	0.8635				
A_o (m^2)	0.05256				
σ_y	0.77				
σ_z	0.82892				
Q_o (l/s)	6				
	Scaling process				
Q_ot (m^3)	32.4	63.81	79.56	101.88	119.52
Advance distance, x, (m)	250	500	650	800	920
Advance time, t, (min)	90	177.26	221	283	332
Scaling factor (F)	2.921	2.450	2.191	2.197	2.181
	Scaled infiltration parameters				
a	0.2264	0.2264	0.2264	0.2264	0.2264
k	0.03882	0.03256	0.02912	0.02920	0.02899
f_o	0	0	0	0	0

Table 6.4: Effect of advance distance on the scaling factor - Sites A and B

Site A						
		Advance distance (m)				
	Q_o(l/s)	250	500	650	800	920
Trial Number		Scaling factor				
1A	6	2.921	2.450	2.191	2.197	2.181
2A	5		1.288	1.277		1.197
3A	3.82	1.573	1.295	1.324	1.224	1.273
4A	3.3		1.287	1.068	1.079	

Site B						
		Advance distance (m)				
	Q_o(l/s)	200	400	500	600	650
Trial Number		Scaling factor				
2B	1.6	0.978	1.002	0.947	0.886	0.871

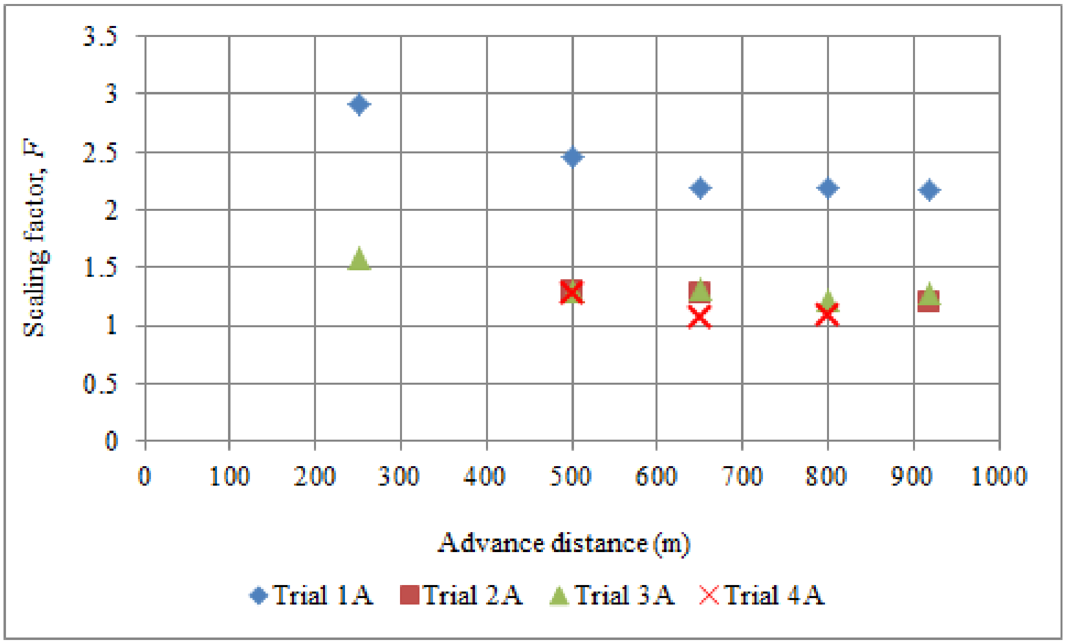


Figure 6.16: Variation of scaling factors with advance distance for Site A

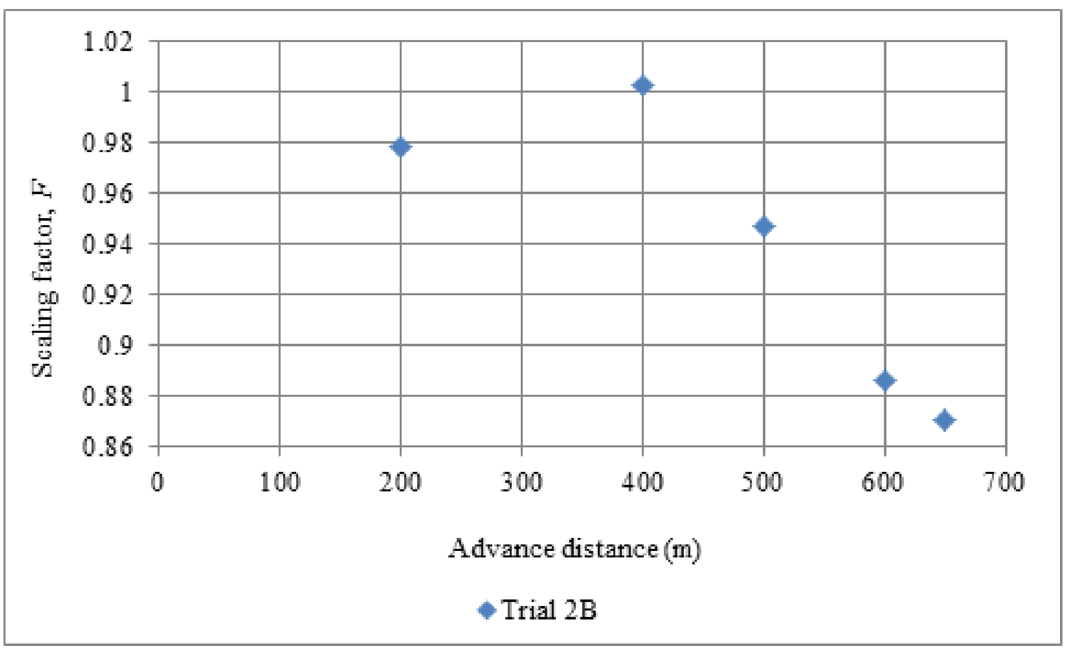


Figure 6.17: Variation of scaling factors with advance distance for Site B

Cumulative infiltration curves were plotted using the scaled infiltration parameters in Table 6.3 (Figure 6.18). This figure suggests a reduction in cumulative infiltration with the increase from 250 to 650 m in the advance distance used in the scaling process. There is a very small change in the predicted cumulative infiltration for advances distances 650, 800 and 920 m.

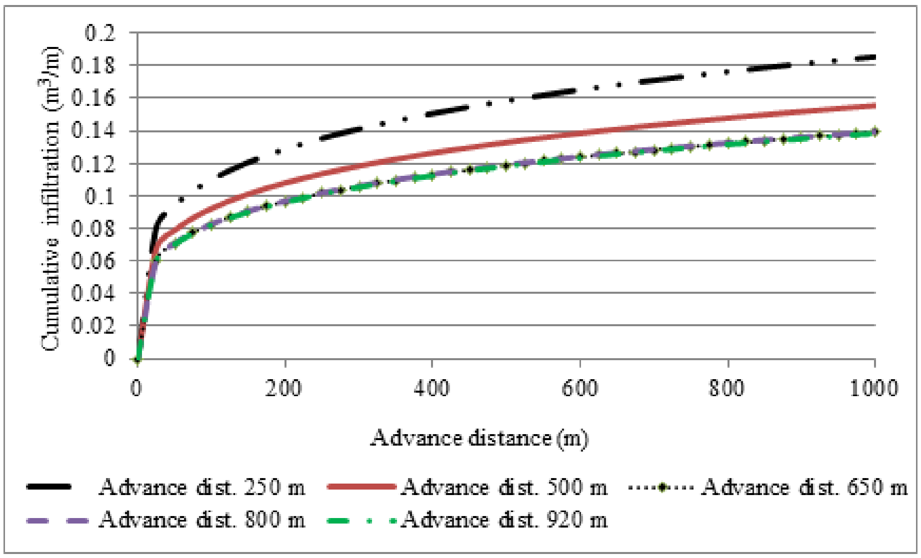


Figure 6.18: Effect of advance distance on predicted cumulative infiltration - Trial 1A

6.7.3 Effect of advance distance on the predicted advance curves

The scaled infiltration parameters calculated in the above section for the various advance distances were used in the SISCO model to generate advance curves (at these distances). In essence, the goal here was to determine the nature of the advance curves the optimisation system would have predicted if alternative advance distances were selected and used in the scaling process. The same variables that were used in the optimisation trials (field details, inflow data, furrow geometry, slope and irrigation deficit) for each respective trial were used in these simulations. In effect the only variables altered were the infiltration parameters.

In order to discern the effect of the advance distance on the predicted advance curves, it was necessary to compare the predicted with the measured advance curves. Since the measured (actual) advance curves related to the actual time to cut off flow, cut of times shown in Table 5.2 were used in the simulations. It was explained in Chapter 5 that the cut off times shown in Table 5.3 were a result of a post-irrigation re-simulation undertaken as a result of the error detected in the original AutoFurrow code.

The results of this analysis are illustrated in Table 6.5 and Figures 6.19 and 6.20 (and Appendix C.5). For Trial 1A, the earliest advance distance investigated (250 m) produced the worst prediction of the advance. Overall, the advance prediction evidently improved with the increase in advance distance used. This is consistent with the findings of previous studies, for example Langat et al. (2008). The improvement is more pronounced at advances distances greater than 500 m (advance distance 500 m was used in the optimisation trials), while the prediction before the 500 m mark very slightly reduced in accuracy.

The optimisation system (using advance distance of 400 m) had a near-perfect prediction of advance up to approximately 450 m (Figure 6.15); beyond that the prediction was grossly inaccurate. In the present case of varying the advance distance however, the downstream-end advance prediction appeared to improve while it clearly suffered in the upstream (Figure 6.20). The effect of the advance prediction in the performance of the optimisation system will be investigated in the next subsection.

Table 6.5: Effect of advance distance on the predicted advance curves - Trial 1A

		Advance distance (m)				
		250	500	650	800	920
Distance (m)	Actual advance time (min)	Predicted advance times (min)				
0	1	0	0	0	0	0
250	90	91	79	73	73	73
500	178	212	183	168	169	168
650	221	291	251	230	231	229
800	283	374	322	295	295	294
920	332	443	381	348	349	347

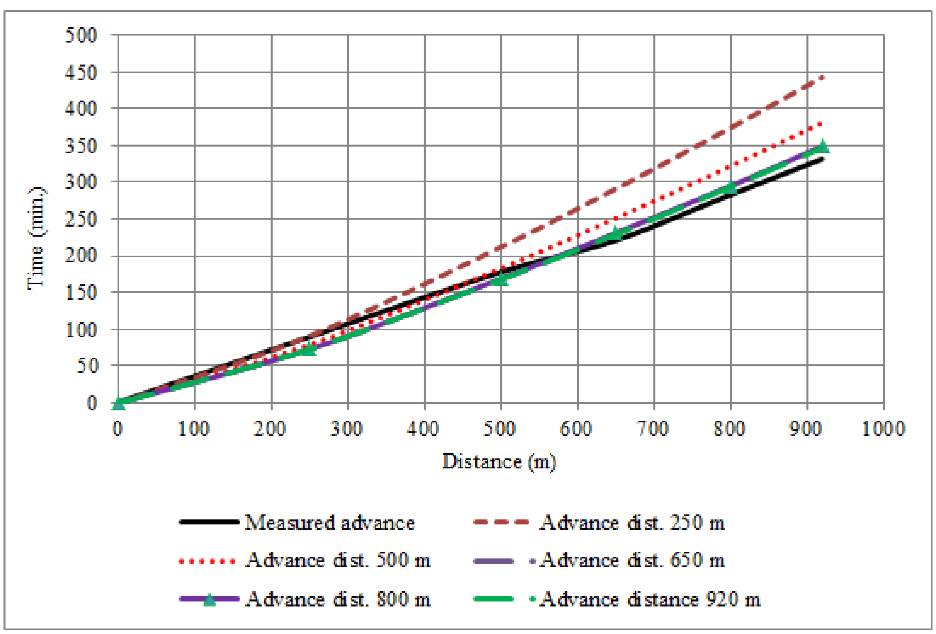


Figure 6.19: Effect of advance distance on the predicted advance curves - Trial 1A

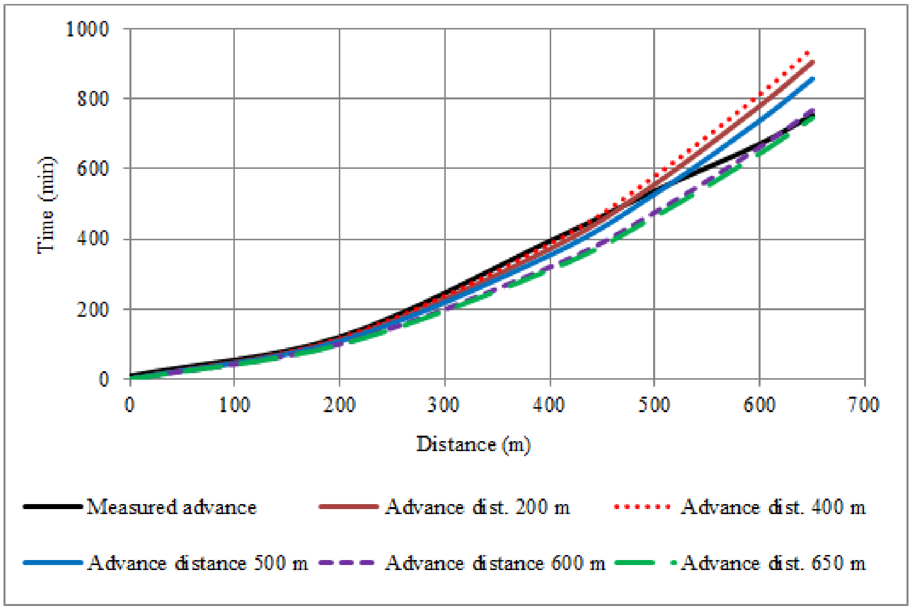


Figure 6.20: Effect of advance distance on the predicted advance curves - Trial 2B

6.7.4 Effect of the advance distance on the performance of the optimisation system

It has been demonstrated above that the scaling factors generally decreased with the increase in advance distance used for scaling and that the increase in the advance distance used for scaling led to an improvement in the prediction downstream and an apparent deterioration in the prediction upstream. Using the same optimisation strategies applied in the optimisation trials, the SISCO model was used to investigate the effect of varying the advance distance on the performance of the optimisation system. As with the advance prediction, the same variables used in the field were maintained (the only variables changed at each advance distance were the scaled infiltration parameters). The results are illustrated in Tables 6.6 and 6.7 (and in Appendix C.5). The cases that failed to satisfy the optimisation strategy are shown as blank columns in the tables.

Table 6.6: Effect of advance distance on the performance of the optimisation system - Trial 1A

Optimisation strategy					
DU $\geq$	55				
RE $\geq$	90				
AE $\geq$	65				
	Advance distance (m)				
	250	500	650	800	920
Predicted Performance (%)					
AE		72	82		82
AE (with 90% recycling)		72	82		82
DU		67	66		67
RE		93	92		93
Inflow volume (m^3)		101	88		88
Drainage (%)		28	18		18
Runoff (%)		0	0		0
Time to cut off (min)		280	244		244

These results suggest that, beyond the advance distances used in the field optimisation trials (500 and 400 m for Sites A and B respectively), the performance of the optimisation system is improved while the corresponding times to cut off flow are reduced (Table 6.6). There is also a reduction in inflow volume and drainage losses. To make the results easily comparable (because the optimisation strategies were different), the maximum AE was determined for RE of $\geq$90% (Figure 6.7). There was poorer performance predicted for advance distances closer to the furrow inlet. This is consistent with the findings of Langat et al. (2008) who concluded that the use of points early in the advance should be avoided because they lead to inaccurate prediction of infiltration.

Table 6.7: Effect of advance distance on the predicted AE and TCO at RE of ≥90%

Site A

Trial Number		Advance distance (m) 250	500	650	800	920
1A	AE(%)	59	72	82	81	82
	TCO (min)	328	280	244	244	244
2A	AE(%)		66	67	72	
	TCO (min)		360	360	328	
3A	AE(%)	69	85	83	90	86
	TCO (min)	456	382	376	344	360
4A	AE(%)		73	89	89	
	TCO (min)		536	440	440	

Site B

Trial Number		Advance distance (m) 200	400	500	600	650
2B	AE(%)	62	59	65	72	74
	TCO (min)	872	904	824	744	728

6.7.5 General discussion

The analysis undertaken in this section has found that the scaling factors generally reduce with the increase in advance distance used in the scaling process performed in the optimisation system, but tend to converge to a constant value. On the other hand, irrigation performance (especially the AE) was found to increase with the increase in the advance distance used in scaling. For some trials (for example Trial 2B - Figure 6.21), there was a near perfect negative correlation between the predicted AE and the scaling factor (R^2 = 0.9989). However, the regression line for the entire set of data (all the five trials controlled by the optimisation system) suggests a correlation coefficient (R^2) of 0.7347 . This is shown in Figure

6.22, with the scaling factors having been scaled down proportionately to allow a direct comparison to be made.

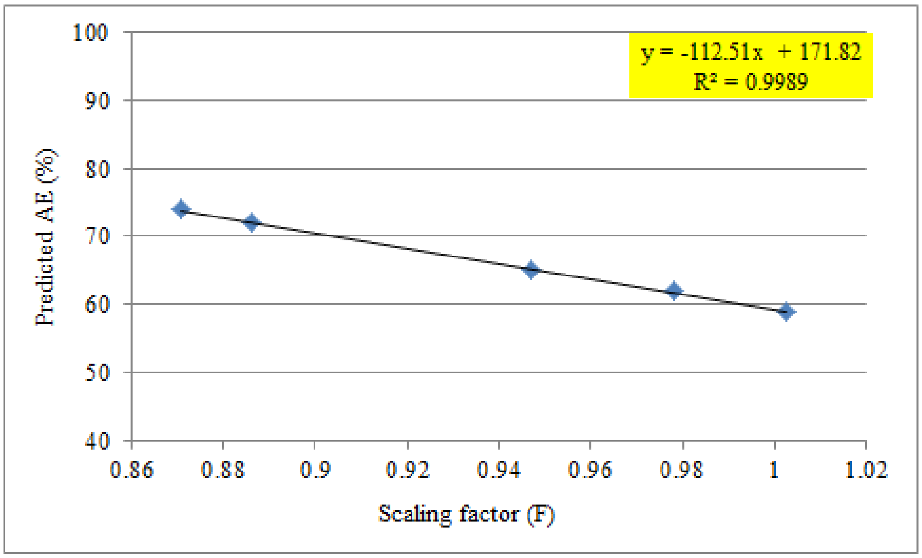


Figure 6.21: Scaling factor versus predicted AE - Trial 2B

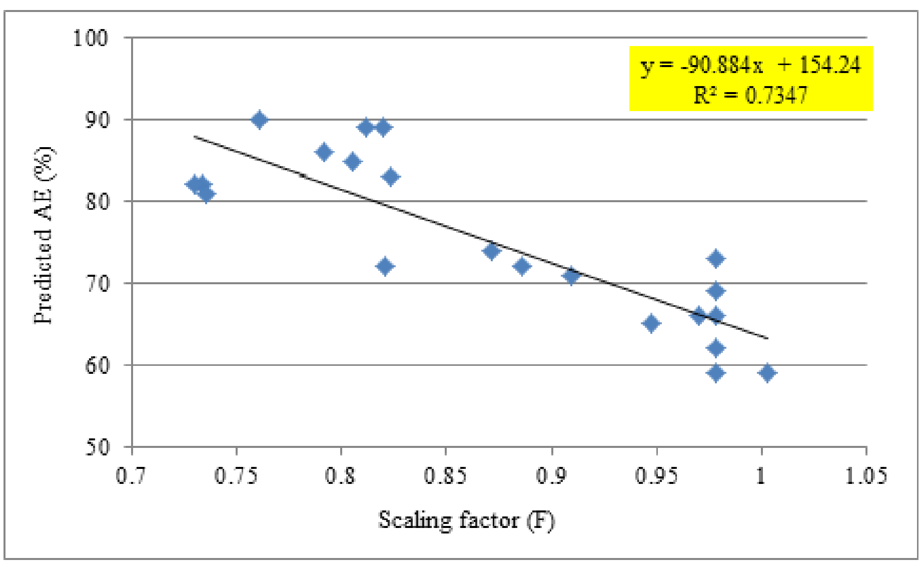


Figure 6.22: Scaling factor versus predicted AE - Sites A and B

Although the use of advance points late in the advance in the optimisation system has been shown to lead to a better performance of the system, it may not be practicable in some cases. This is because in order to achieve optimum performance it may mean that the inflow is terminated just after the advance has passed the midpoint. This is illustrated in Table 6.2 (and Appendix B) where for example in Trial 1A, the optimum time to cut off flow is determined to be 190 m.

The fact that the the predicted advance in all the trials was slightly slower that the actual (especially from the midway point and beyond) is of significant importance in this analysis. The trends observed from these curves will not necessarily translate to other curves exhibiting different infiltration characteristics. In the next chapter a similar analysis will be undertaken using data from a different trial site, potentially with different advance patterns.

6.8 Selection of the model curve

It has been explained in Chapter 3 that, for some trials a furrow deemed representative was selected and evaluated over an irrigation event to obtain the parameters of a model infiltration curve to be used in the scaling procedure. On an evaluation of 44 furrow irrigation events on two different fields, Khatri & Smith (2006) concluded that varying the model curve did not have any significant impact on the scaled infiltration curves. However in the results presented in Chapter 5 the cumulative infiltration curves of the eight furrows measured are variable in shape. In such a case it is a great challenge to physically identify a curve that would be truly representative.

To illustrate this point the cumulative infiltration curves of the eight furrows monitored (Trial 1A) for purpose of the complete evaluation of the irrigation will be used (Figure 6.23 and Appendix C.5). Two distinct shapes of curves can be seen in this figure: F4, F5 and F6 show a rapid initial infiltration followed by a low to constant final infiltration, and the rest of the furrows depict a more traditionally shaped curve with infiltration rate declining with time. Furrows F4, F5 and F6 are typical of heavy cracking clays which was the dominant soil type at the site. F5 was selected as the model curve.

The difference in shapes of these curves could have been partly caused by the inter-furrow spatial variability of the soil infiltration characteristics. For instance F8 was wheel-tracked and it is shown in Figure 6.23 as having the least infiltration capacity. Another possible contributing factor to the difference in shapes of the curves is the uncertainty that exists in the measured advance.

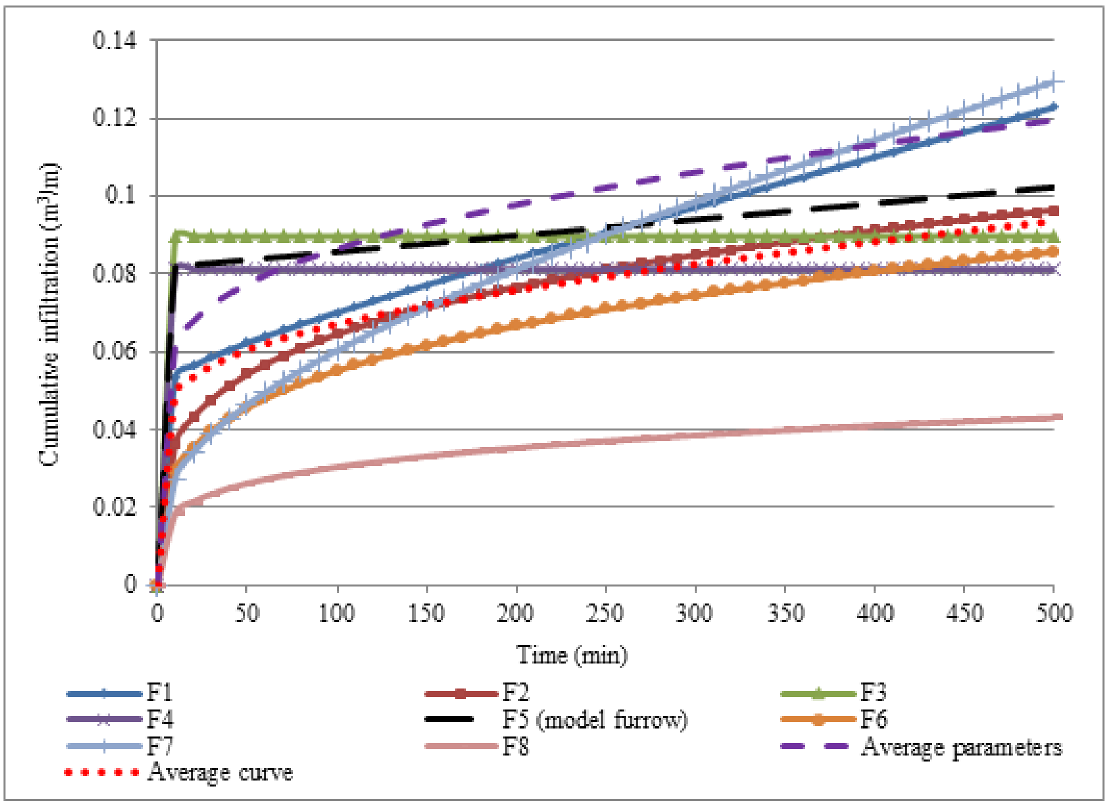


Figure 6.23: Model curve and average curves in relation to rest of the curves (Trial 1A)

The shape of the model infiltration curve plays a major role in the scaling process and the overall performance of the real time optimisation. This is because the shape will influence the scaled infiltration characteristic estimates which are used to assess the irrigation performance of the optimisation system. As indicated in subsection 3.4.2, the fact that parameter 'a' in the Kostiakov-Lewis equation is assumed constant (and therefore not scaled) means that the scaled infiltration curves will bear the same shape as the model infiltration curve (Figures 6.12 and 6.13). Hence it follows that if the model curve is markedly different in shape from the actual infiltration curve in the trial furrow, significant errors in the estimates of the scaled infiltration curves are likely to occur. This will inevitably impact on the predicted performance and time to cut off.

An investigation was also undertaken to explore alternative methods of selecting the model curve. The two methods identified were: (i) averaging the infiltration parameters (a, k and f_o) of all the eight furrows to obtain the model curve; and (ii) using the average shape of the cumulative infiltration parameters of the eight furrows as the model curve.

The first approach is relatively straight-forward as it entails a direct use of the average infiltration parameters in the determination of the model infiltration curve. The cumulative infiltration curve resulting from this procedure is plotted on Figure 6.23. The curve lies above most of the other curves and hence it is not an ideal representative curve although its shape appears reasonable. The conclusion from this is that averaging of parameters lead to significant errors in the estimation of infiltration and should not be used.

The second approach basically means determining the average curve amongst the group of curves and this is also shown in Figure 6.23. This curve is located approximately in the middle of the rest of the curves and is of a representative or 'average shape'. The logic behind choosing a furrow with average characteristics or shape in the optimisation system trialled in the field is that optimisation is based on one advance measurement in a single furrow and a model curve. Since it has been demonstrated that the model curve has an impact on the scaling factor (Langat et al. 2008), an average curve therefore is likely to give a better prediction of performance for the group of furrows. A better average curve may be obtained by determining the average for the furrow set as well as all the irrigations in the season.

The challenge with this second method is in deducing the infiltration parameters (a, k and f_o) from the average shape. A new procedure designed to simplify this process will now be described. Figure 6.24, containing two cumulative infiltration curves, will be used to illustrate this process.

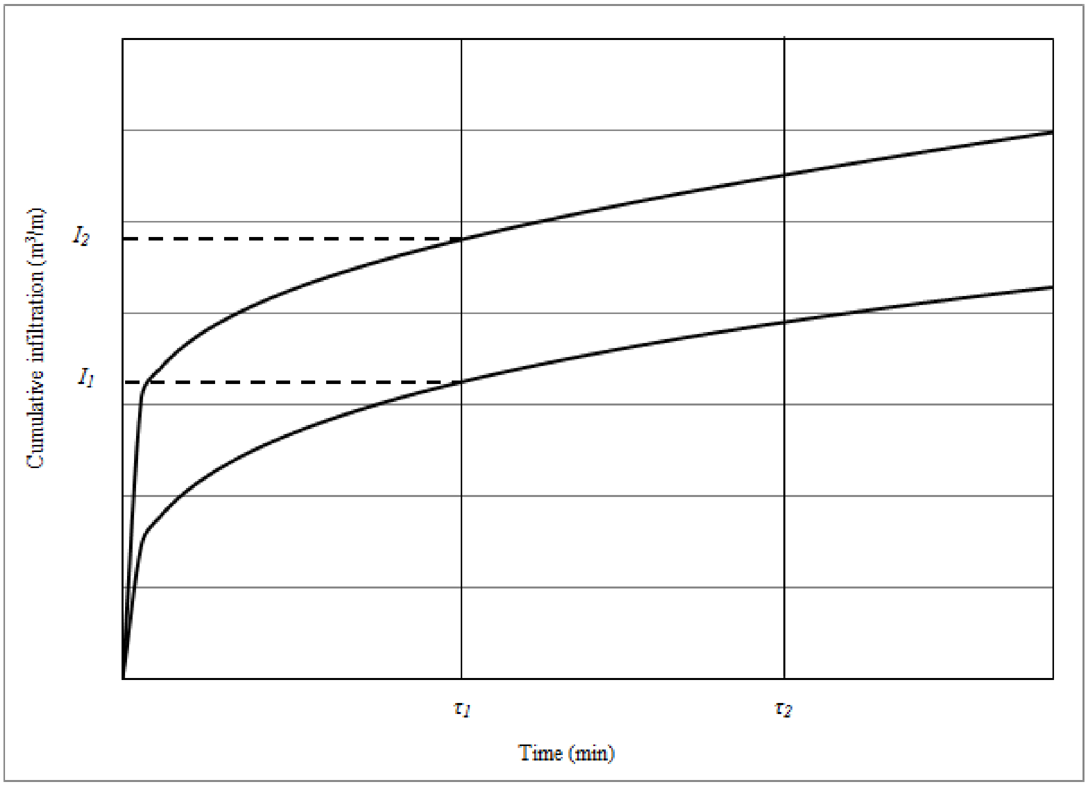


Figure 6.24: Determination of the model curve from the average shape

To maintain consistency in this dissertation, the Kostiakov-Lewis equation will be used to describe the infiltration process. At time τ_1, the cumulative infiltration of the two curves may be expressed using two simultaneous equations:

$$I_1 = k_1 {\tau_1}^{a_1} + f_{0_1} \tau_1 \tag{6.1}$$

$$I_2 = k_2 {\tau_1}^{a_2} + f_{0_2} \tau_1 \tag{6.2}$$

where all the terms are as described in Chapter 2. The subscripts *1* and *2* refer to curve 1 and 2 and times 1 and 2 as shown in Figure 6.24.

The average cumulative infiltration, I_{av}, at time τ_1 is given by:

$$I_{av} = \frac{k_1 {\tau_1}^{a_1} + k_2 {\tau_1}^{a_2}}{2} + \frac{(f_{0_1} + f_{0_2})\tau_1}{2} \tag{6.3}$$

For any number of curves n, Eqn. 6.3 can be rewritten as:

$$I_{av} = \frac{k_1 {\tau_1}^{a_1} + k_2 {\tau_1}^{a_2} + ...k_n {\tau_1}^{a_n}}{2} + \frac{(f_{0_1} + f_{0_2} + ...f_{0_n})\tau_1}{n} \tag{6.4}$$

The two parts on the right hand side of Eqn. 6.4 will now be treated separately. The first group of terms consists of the parameters k, τ and a. Therefore:

$$k\tau^a = \frac{(k_1 {\tau_1}^{a_1} + k_2 {\tau_1}^{a_2} + ...k_n {\tau_1}^{a_n})}{n} \tag{6.5}$$

Taking logarithms on both sides of Eqn. 6.5 results in the following equation:

$$log(k) + a{*}log_{\tau_1} = log(f_n \tau_1) \tag{6.6}$$

It follows that the corresponding equation at time τ_2 would be:

$$log(k) + a{*}log_{\tau_2} = log(f_n \tau_2) \tag{6.7}$$

where $f_n\tau_1$ represents all terms on the right hand side of Eqn. 6.5 respectively with a similar equation for $f_n\tau_2$. Eqn. 6.6 and Eqn. 6.7 are a set of simultaneous equations. Subtracting Eqn. 6.7 from Eqn 6.6 results in a solution for parameter a:

$$a(log_{\tau_1} - log_{\tau_2}) = log(f_n\tau_1) - log(f_n\tau_2) \tag{6.8}$$

$$a = \frac{log(f_n\tau_1) - log(f_n\tau_2)}{(log_{\tau_1} - log_{\tau_2})} \tag{6.9}$$

Once a solution for parameter a is found, parameter k can be solved by substituting parameter a in either Eqn. 6.6 or Eqn. 6.7. It is clear from Eqn. 6.4 that the average value for parameter f_o is obtained by the direct mean of all the f_o terms.

Based on the above equations, a simple Excel program was formulated to speed up the search for the parameters a, k and f_o which describe the average curve of the entire set of eight cumulative infiltration curves.

6.9 Multi-furrow evaluation

Results from the multi-furrow evaluations (Table 6.8 and Appendix C.5) using data collected during the complete irrigation evaluation process are presented as follows:

- performance obtained using the model or trial furrow;
- combined performance of the group of eight furrows; and
- range of the performance obtained from the eight furrows. The complete set of results showing individual furrow performance is shown in Appendix C.7.

This new feature in the SISCO model provides an opportunity to compare the irrigation performance based on a single model furrow vis a vis the combined irrigation performance of a group of furrows. The real-time optimisation and control system uses measurements obtained from one furrow to make decisions on the entire set of furrows and hence multi-furrow performance evaluation is particularly useful.

Table 6.8 and Appendix C.7 show that the key performance measures (AE, RE and DU) for the model furrow were higher than the corresponding values obtained for the combined set of eight furrows. The table also shows that there can be a wide range in irrigation performance among furrows brought about by spatial variability in the soil infiltration characteristics. In particular the wheel-tracked furrows (furrow number 8 in Trials 1A, 2A, 3A and 4A) in general appeared to have faster advance and lower infiltration compared to the rest of the furrows. These furrows are largely responsible for the wider range in irrigation performance among the eight furrows.

It therefore follows that the true irrigation performance of the entire set of furrows controlled using the real time control system, which is based on advance measurement at a single point in the model furrow, would be expected to be slightly lower than those presented in Table 5.3. This further confirms the conclusion arrived at above that the choice of the model curve is important as it can affect the performance of the optimisation system.

The irrigation performance predicted by the optimisation system could possibly be adjusted to reflect the 'true' performance of the set by introducing a factor similar to the scaling factor described in Chapter 3. This might involve adjusting the TCO for the model furrow to that required to give optimum performance for the set. This was not attempted in the present research (due to time limitation), but it is certainly an interesting idea worth exploring in the future.

Table 6.8: Multi-furrow performance evaluation

	Performance measure						
Trial no. and scale	AE (%)	RE (%)	DU (%)	AE recy (%)	Runoff (%)	Drainage (%)	Inflow (m^3)
1A							
Model furrow	50.8	100.0	99.6	87.3	46.4	2.6	152.6
Entire set	48.0	94.4	71.2	79.4	44.0	7.9	1221.2
Individual furrows	27.9-50.8	54.9-100	90.4-99.9	66.3-89.7	25.9-72.0	0-23.2	152.6-152.7
2A							
Model furrow	65.2	100.0	95.4	69.4	6.7	28.0	119.1
Entire set	60.5	92.1	68.2	77.6	24.5	14.9	945.3
Individual furrows	51.2-66.0	77.5-100	77.1-99.9	68.8-91.7	0-61.3	0-38.2	89.9-90.3
3A							
Model furrow	76.0	100.0	98.5	87.2	14.2	9.4	104.5
Entire set	74.8	98.3	84.9	87.8	16.5	8.7	836.3
Individual furrows	70.5-76.1	92.6-100	90.2-99.8	82.2-96.0	8.4-29.4	0-15.4	104.5-104.6
4A							
Model furrow	75.5	100.0	99.9	96.5	24.2	0.2	115.7
Entire set	67.5	89.6	62.7	89.4	27.2	5.1	926.2
Individual furrows	39.8-75.5	52.7-100.0	84.1-99.9	85.2-96.5	12.7-48.5	0-11.8	115.6-116.6
1B							
Model furrow	57.1	89.1	39.0	57.1	0.0	42.8	89.1
Entire set	54.5	85.0	28.1	56.3	3.6	41.8	712.8
Individual furrows	51.5-64.1	79.8-100	13.1-99.9	51.1-86.7	0-28.9	6.9-48.8	89.1 89.1
2B							
Model furrow	63.6	100.0	81.0	67.6	6.6	29.8	89.9
Entire set	60.2	94.8	66.5	73.2	19.8	20.0	719.8
Individual furrows	38.6-63.6	60.8-100	72.7-99.7	61.7-86.2	0-61.3	0-38.2	89.9-90.3
3B							
Model furrow	82.2	99.7	90.2	88.2	7.6	10.2	69.3
Entire set	80.9	97.7	83.6	88.8	9.8	9.1	551.7
Individual furrows	73.5-83.0	89.2-100	46.7-98.5	73.5-97.5	0-18.4 18.4	0.2-26.4	68.8-69.3
4B							
Model furrow	62.6	93.9	99.1	94.2	37.3	0.0	96.4
Entire set	58.7	88.0	43.4	70.1	18.1	23.0	771.2
Individual furrows	32.2-66.7	48.3-100.0	30.5-99.7	56.5-94.2	0-67.7	0-43.2	96.4

6.10 Conclusions

The SISCO model was used in this chapter to investigate the effect of alternative management strategies using field data collected for this research. With a fixed Q, deficit and model curve, simulations were undertaken to identify the best irrigation performance of the actual irrigations (as determined using the conventional furrow irrigation evaluation methodologies) as well as the performance determined by the automated furrow system developed in this study. In both cases the RE was set at $\geq$90%.

The next evaluations focussed on varying Q (keeping model curve and deficit as constant) and assessing the impact on AE, RE and TCO. A sensitivity analysis was undertaken to investigate the effect of varying the flow rate irrigation deficit on AE and TCO. An analysis of the infiltration scaling process , the effect of using an alternative model curve, location of the advance meter and multi-furrow evaluation were also undertaken.

There was no demonstrable benefit of using an alternative objective function in the optimisation field trials. It is concluded the scope of performance of the system was limited by the scaling procedure used to estimate the soil infiltration parameters from a model infiltration curve. However, the post irrigation evaluation of the actual irrigations revealed a significant potential for improvement in irrigation performance. It is proposed that a simpler objective function possibly containing AE and RE fixed at some desired level can deliver accurate prediction of the irrigation performance and add to the robustness of the optimisation process.

With a constant TCO, it was demonstrated that there are potential gains in AE in reducing flow rate but at an expense of reduced RE. In conformity with previous studies, AE was found to increase while the optimum TCO decreased with the increase in inflow. It was found that the predicted TCO was not very sensitive to the irrigation deficit. However any change in the irrigation deficit altered the AE predicted.

Differences were noted between the scaled and actual advance curves and cumulative infiltration curves. The scaling procedure used (based on the volume balance model) as well as the possible variability between the soil infiltration characteristics of the two halves of the field) were thought to be possible reasons. The inaccurate scaling process ultimately reduced the scope for improvement of the real time optimisation trials. On average, SISCO scaling (based on the full hydrodynamic model) performed better than the scaling based on the volume balance model.

Deriving the model curve by directly averaging the infiltration parameters (a, k and f_o) of the furrows in an irrigation set lead to an unacceptable inaccuracy and should not be used. Model curve obtained by averaging the shape of all the infiltration curves appears to be the most representative.

Although it would be desirable to have an advance point used in scaling further down the furrow (it has been suggested that doing so improves the scaling), this may not be practical in some cases because optimum time to cut off flow may be when the advance has just past the halfway point. Therefore an advance point further down the furrow may not provide enough time to undertake the optimisation.

It can be inferred from the multi-furrow analysis undertaken that the true performance of the real time optimisation may be slightly lower than predicted in Chapter 5. The combined performance of the eight furrows monitored was found to be lower than the performance predicted using the model (single) furrow. Further work is recommended to develop a procedure for adjusting the performance of the optimisation system (which is based on a model furrow) to reflect the true performance of the furrow set.

Chapter 7

Final Field Trials (2011/12 irrigation season)

7.1 Introduction

A second and final set of field trials for this research were undertaken during the 2011/12 irrigation season in St George (Site C) and Dalby (Site D), both in Queensland Australia. In St George the trial was undertaken in the same cotton property that was used in the 2010/11 irrigation season but a different set of furrows was used. The details of these two field sites have been described in Chapter 4. It has also been noted in Chapter 4 that extreme weather conditions experienced in the 2011/12 irrigation season severely impacted on the field trials. The uncharacteristically heavy rains and flooding events experienced at the two sites reduced the total number of trials undertaken from eight down to three (four trials had been planned for each site).

The motivation behind the decision to undertake a second set of field trials was twofold: to test the corrected version of the optimisation software (AutoFurrow) and to explore the performance of the optimisation system on a different soil type.

As indicated in Chapter 5, an error in the code of the AutoFurrow software was identified after the 2010/11 field trials and subsequently corrected. Hence it was vital to test the new version of the software in the field trials. Secondly, it was felt necessary to test and compare the performance of the optimisation system on a different soil type potentially possessing different infiltration characteristics. The soil type at the new site (Site D) was felt to be sufficiently different from the St George site for comparison purposes.

The field trials in the previous irrigation season and the subsequent analysis (Chapter 6) provided the basis for the changes introduced in the methodology used in these second trials. The changes effected are enumerated below:

- The procedure described in Chapter 6 (section 6.8) and specifically the Excel program was used in the selection of the model curve applied in the optimisation trials. This is explained further in the section below.
- A simpler objective function consisting of only the RE and AE was used in the optimisation. The analysis in Chapter 6 showed that this would not compromise the accuracy of the optimisation system but would potentially improve the robustness of the optimisation process.
- The PST was not used for flow measurement in the second set of trials (only the ultrasonic and siphon flow meter were used instead). The former was used to measure discharge through the PTB while the latter was used to measure flow through siphons. The decision to discontinue the use of the PST followed from the challenges experienced in its calibration especially in conditions where the level of water in the field side of the head ditch was variable.

The version of the AutoFurrow software used in these trials still used the volume balance approach for scaling. All other field procedures were unchanged from the first season's trials.

7.2 Model infiltration curve and infiltration scaling

It has been indicated in the introduction above that changes were made in the method used to select the model infiltration curve used in the AutoFurrow software as inputs to the scaling process. Using an average curve as the model curve was proposed in Chapter 6 as it is likely to lead to more accurate scaled infiltration characteristics. The process of averaging the curves was made easier by composing a simple Excel program to undertake the calculation.

The model curve used in the only trial undertaken at Site C was obtained by taking the average curve of the four model curves obtained from the same field (but different set of furrows) during the 2010/11 irrigation season field trials (Table 5.1, Chapter 5). The average curve in relation to the rest of the curves is shown in Figure 7.1.

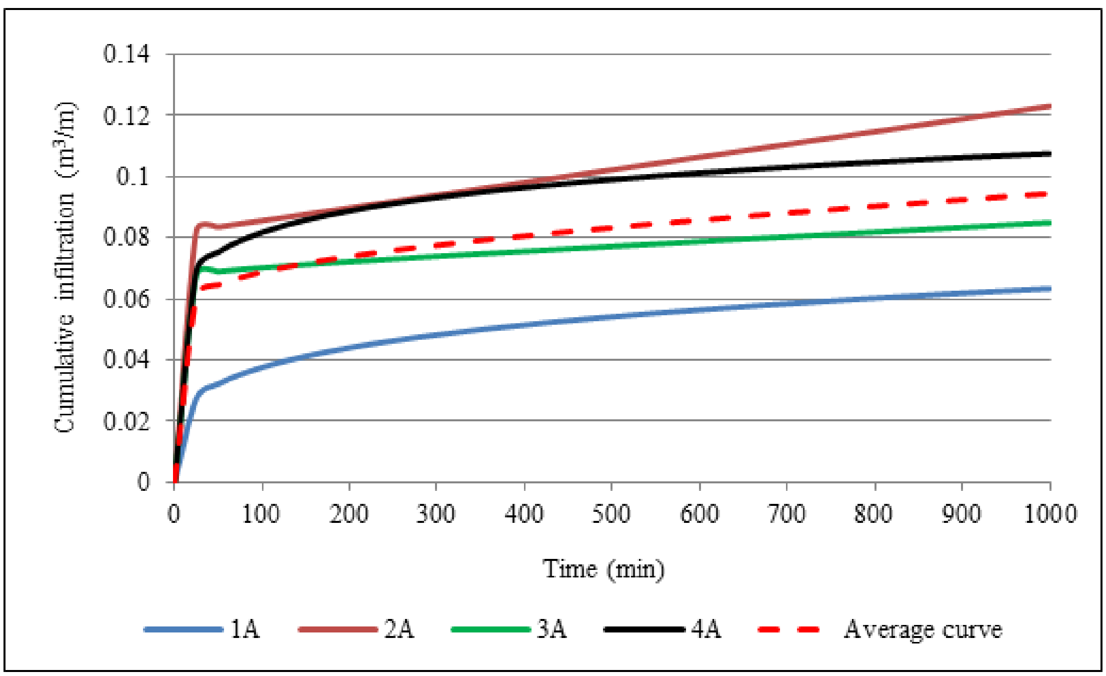


Figure 7.1: Trial 1C model infiltration curve

In the case of 1D (the initial trial at this site), the model curve used was obtained from evaluations done previously on a nearby cotton property during the 2009/10 irrigation season. The soil type at that site and Site D are similar, and in the absence of any data from the present site, the data was assumed applicable for the purpose of the initial evaluation. The model curve for the second trial at site D (Trial 2D) was obtained by averaging the four actual infiltration curves obtained from the first trial (Figure 7.2).

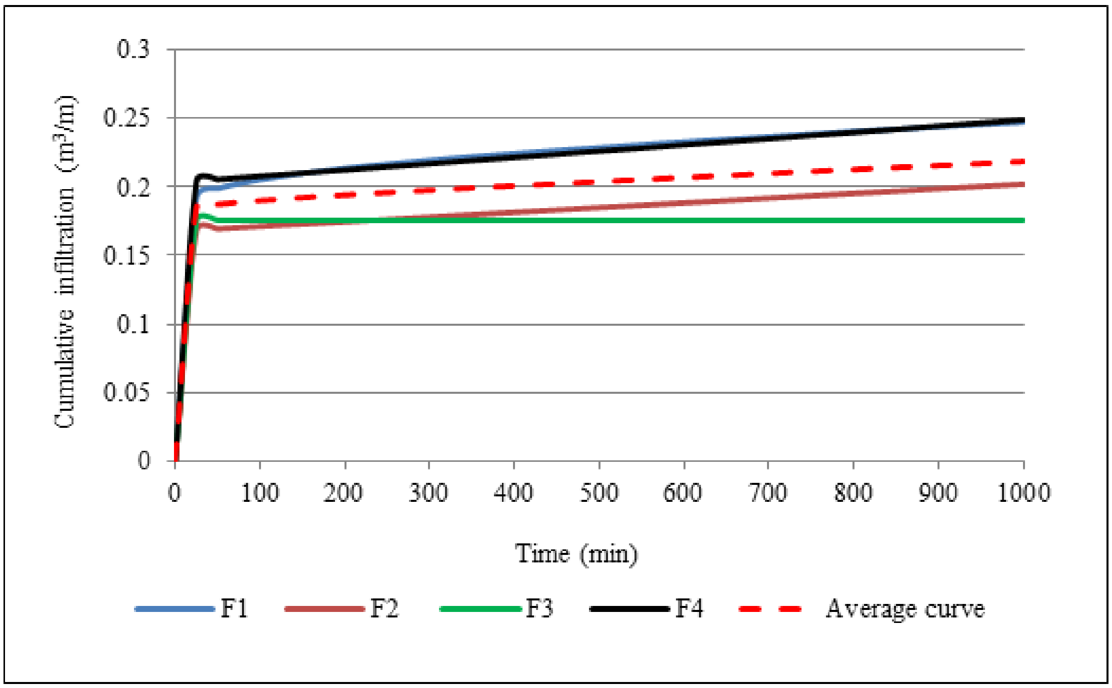


Figure 7.2: Trial 2D model infiltration curve

It is clear from Figures 7.1 and 7.2 that none of the four individual infiltration curves can be as representative (in terms of shape) as the average curve. And since the control measures taken in the optimisation system equally affects the entire set of furrows, the average curve has the best chance of delivering the best performance for the entire set.

The volume balance infiltration scaling was maintained in AutoFurrow as explained above, as was the midway (down the furrow) advance distance. The model and scaled parameters, the advance (both distance and time) and the scaling factors relating the three trials undertaken during the irrigation season are summarised in Table 7.1.

Table 7.1: Model and scaled parameters

	Site C	Site D	
Trial number	1C	1D	2D
Model curve			
a	0.07700	0.03050	0.01087
k	0.04731	0.05261	0.17825
f_o	0.00001	0.00031	0.00003
Advance			
Distance (m)	500	300	300
Time (min)	278	398	445
Scaling factor	1.44704	1.32686	0.98860
Scaled parameters			
a	0.07700	0.03050	0.01087
k	0.06846	0.06980	0.17621
f_o	0.00002	0.00041	0.00003

7.3 Irrigation performance

7.3.1 Prediction of the optimisation system

All the hardware and software used in the trials performed as expected. The predicted performances of the three trials controlled using the optimisation system are shown in Table 7.2. As was the case in the 2010/11 irrigation trials, the evaluations were based on the flow rates (constant) normally used by the irrigator (that is, no attempt was made to vary the flow rate).

While AE and RE predicted were $> 70\%$ and $> 90\%$ respectively for Trials 1C and 2D, the predicted AE for Trial 1D was $< 50\%$ with a DU of 0%. It will be noted that the model curve used in this trial was a guesstimate based on data obtained from a different field site (albeit with similar soil characteristics) in a different irrigation season. This will be discussed in more detail later in this chapter.

Table 7.2: Performance predicted by the optimisation system

	Site C	Site D	
Trial number	1C	1D	2D
Time to cut off (min)	440	798	760
Inflow (l/s)	3.83	2.6	2.4
Deficit (mm)	80	80	80
Optimisation strategy			
RE $\geq$	90	61	90
AE	Maximum	Maximum	Maximun
Predicted Performance (%)			
AE	71	47	80
AE (with 90% recycling)	71	47	80
DU	67	0	68
RE	92	61	91
Inflow volume (m^3)	101.11	125	110
Drainage (%)	29.04	54	20
Runoff (%)	0	0	0

7.3.2 Performance based on complete evaluation

A complete performance evaluation (similar to the better known Irrimate^{TM} evaluation) was undertaken (in addition to the optimisation process) in all field trials. As explained in Chapter 5, the infiltration parameters used in the evaluation process were obtained from the same model furrow which was used for the optimisation procedure (Table 7.3).

Table 7.3 shows that the actual AE (determined from actual infiltration) and RE were greater than 74 and 94 % respectively for the three trials. The simulations suggested a runoff of 10% for Trial 1D while the other two had nil.

Table 7.3: Actual irrigation performance

	Site C	Site D	
Trial number	1C	1D	2D
Time to cut off (min)	440	798	760
Inflow (l/s)	3.83	2.6	2.4
Deficit (mm)	80	80	80
Infiltration parameters			
a	0.01302	0	0.05431
k	0.07980	0.16775	0.13894
f_o	7.03E-05	3.43E-05	0
Actual Performance (%)			
AE	74	77	83
AE (with 90% recy.)	74	85	83
DU	78	96	80
RE	96	100	94
Inflow volume (m^3)	101	125	110
Drainage (%)	26	13	17
Runoff (%)	0	10	0

7.3.3 Difference in performance

As suggested in the first chapter of this dissertation, the success of a real time optimisation and control of furrow irrigation system lies in its ability to use a limited amount of data to simulate and optimise an irrigation event and make decisions (such as the time to cut off flow) while the same irrigation event is still underway. The use of a limited amount of data (as opposed to the conventional Irrimate^{TM} process which uses the full set of data) means that there might be differences in the predicted and the actual performances. The scaling procedure was used in this research because past studies (e.g. Khatri and Smith 1996) have suggested that it is capable of minimising these differences.

To put these into context, the ability of the predicted performances (Table 7.2) to mirror the actual performances (Table 7.3) is an indication of the success of the scaling procedure and ultimately the optimisation system. The cumulative infiltration curves and the advance curves which are used to determine the performance of an irrigation event will be discussed later in this chapter.

The difference between the predicted AE and RE (Table 7.2), and the actual AE and RE (Table 7.3) was $\leq 4\%$ for Trials 1C and 2D. Anecdotal evidence has shown that these two irrigation performance measures (AE and RE) are arguably the most applicable in broad-acre irrigation practices. The relatively minor difference is a sharp contrast to the differences experienced between the predicted and the actual performances during the 2010/11 irrigation season trials (Tables 5.3 and 5.4, Chapter 5).

In the 2011/12 irrigation season trials, Trial 1D registered a significant difference between the predicted and the actual irrigation performance. For instance, while the optimisation system predicted a DU of 0% (Table 7.2), simulation based on the actual infiltration (Table 7.3) suggested a DU of 96%! This is a strong indication of the inaccuracy of the scaling procedure and ultimately the optimisation process based on the model inputs used in this particular trial. Since the methodology used in the three trials was exactly the same, it seems logical to conclude that the cause of the significant differences in performances was the model infiltration curve used for this trial. More evidence will be given later in this chapter to confirm this assertion.

7.4 Cumulative infiltration and advance curves

7.4.1 Actual and scaled cumulative infiltration curves

The actual and scaled cumulative infiltration curves for the three trials are shown in Figures 7.3 to 7.5. These are simulated volumes of water infiltrating into the soil profile at various times based on the actual measured infiltration (actual cumulative infiltration curves) and scaled infiltration (scaled cumulative infiltration curves) per metre width. The amount of water that has infiltrated into the soil profile is one of the most important determinants of the performance of an irrigation event. As with the case of irrigation performance explained in section 7.3 above, a scaled cumulative infiltration curve that matches (in both shape and magnitude) the actual cumulative infiltration curve is an indication of an accurate scaling process.

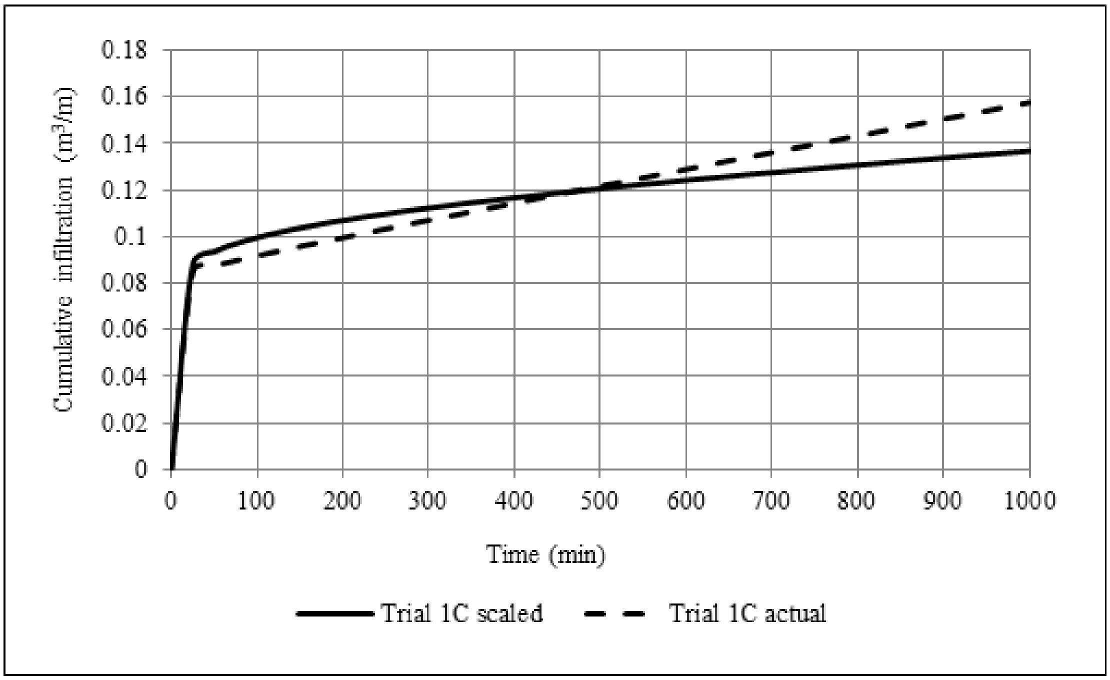


Figure 7.3: Actual and scaled cumulative infiltration curves - Trial 1C

Minor differences still exist between the predicted and the actual cumulative infiltration curves obtained from the one trial undertaken in St George (Figure 7.3). However the differences are much smaller than experienced in the 2010/11 irrigation season trials (section 6.5, Chapter 6). The model infiltration used here was obtained from a different set of irrigation furrows to the 2010/11 irrigation season.

There is virtually no resemblance between the scaled and the actual cumulative infiltration curve obtained in the first trial in Site D (Figure 7.4). This was also reflected in the significant difference between actual and the performance predicted by the optimisation system (section 7.3 above). As indicated earlier the model curve used here originated from a different field site.

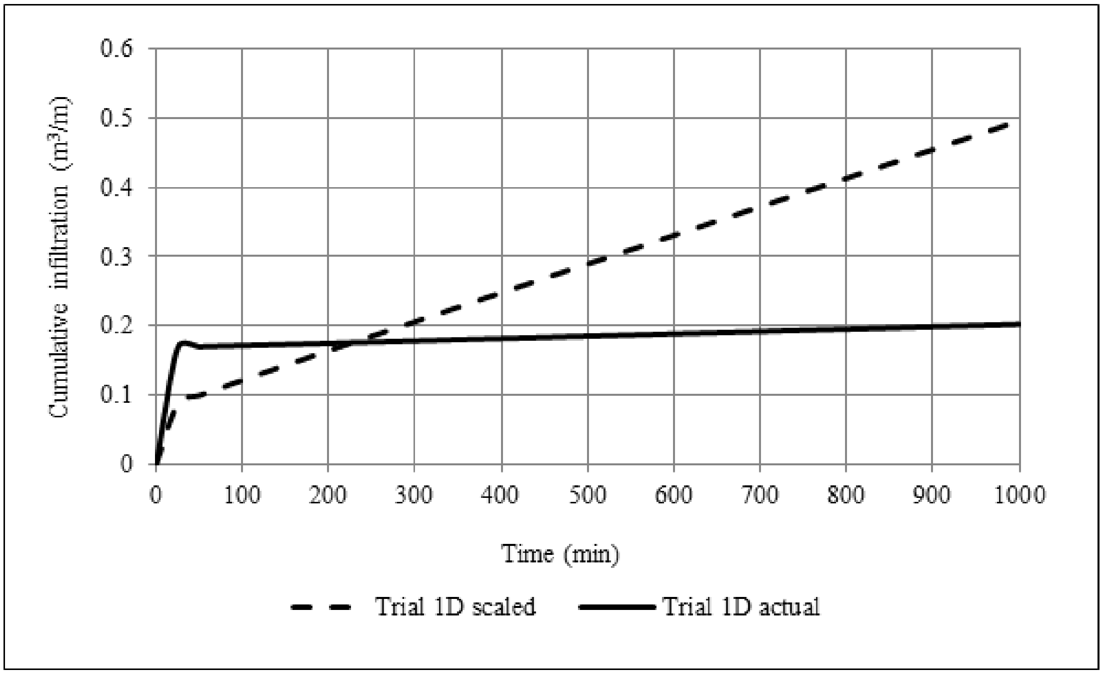


Figure 7.4: Actual and scaled cumulative infiltration curves - Trial 1D

The scaled and the actual cumulative infiltration curves in the case of Trial 2D bear the same shape and are very close to each other (Figure 7.5) as was the case with the corresponding irrigation performances (Section 7.3 above). It has been stated earlier that the model infiltration curve used here was obtained from the complete evaluation undertaken for Trial 1D (same set of furrows). The scaling procedure determined the scaling factor for this trial to be almost 1 (Table 7.1), implying there was little difference in magnitude between the model curve and the actual curve. It is reasonable to conclude that the improved selection of the model curve is responsible for such a close fit and subsequently little difference between the actual and the scaled irrigation performance.

7.4.2 Actual and scaled advance curves

The advance curves depict the rate of movement of water along the length of the furrow. A fast advance means less water is infiltrating into the soil profile, and vice versa. For the purposes of complete irrigation evaluations, the actual advance was measured by using between 5 and 7 advance meters distributed at varying intervals along the length of the set of furrows (8 for Site C and 4 for Site D). The SISCO model (which uses the full hydrodynamic model) was used to predict the advance in the case of the optimisation trials.

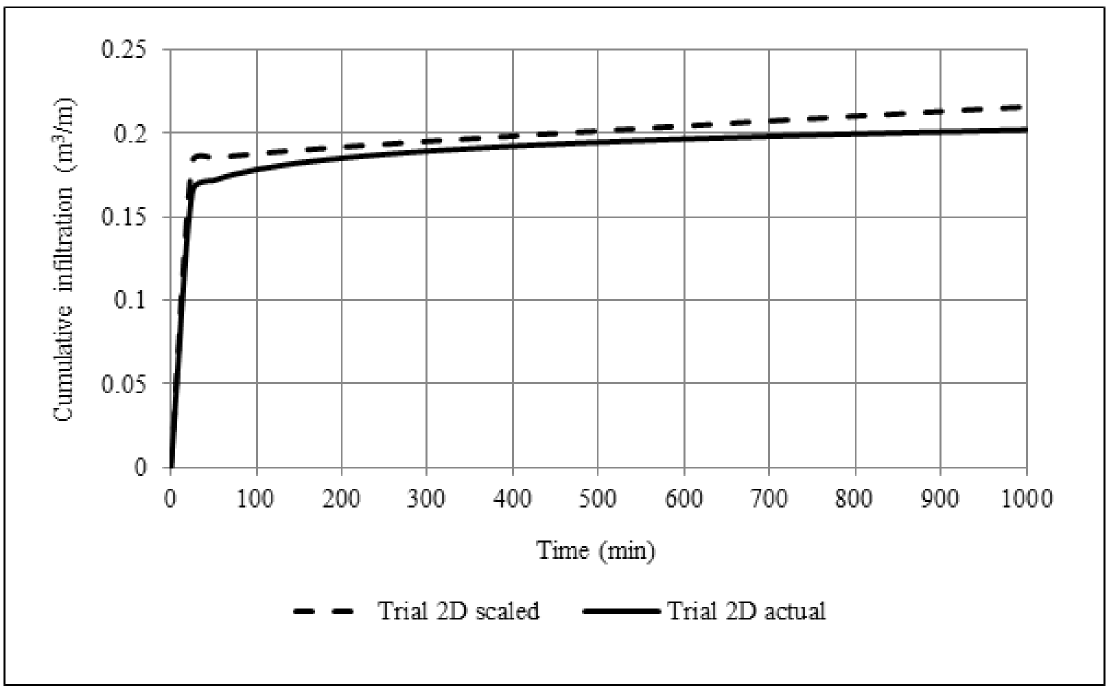


Figure 7.5: Actual and scaled cumulative infiltration curves - Trial 2D

In the real time optimisation system, the predicted advance curves are used to predict the cumulative infiltration that occurs with time along the length of the furrow. It then follows that a good prediction of the advance leads to a better prediction of cumulative infiltration and ultimately a better indication of the expected irrigation performance. Therefore it is clear that an accurate prediction of the advance is vital to the success of the optimisation system.

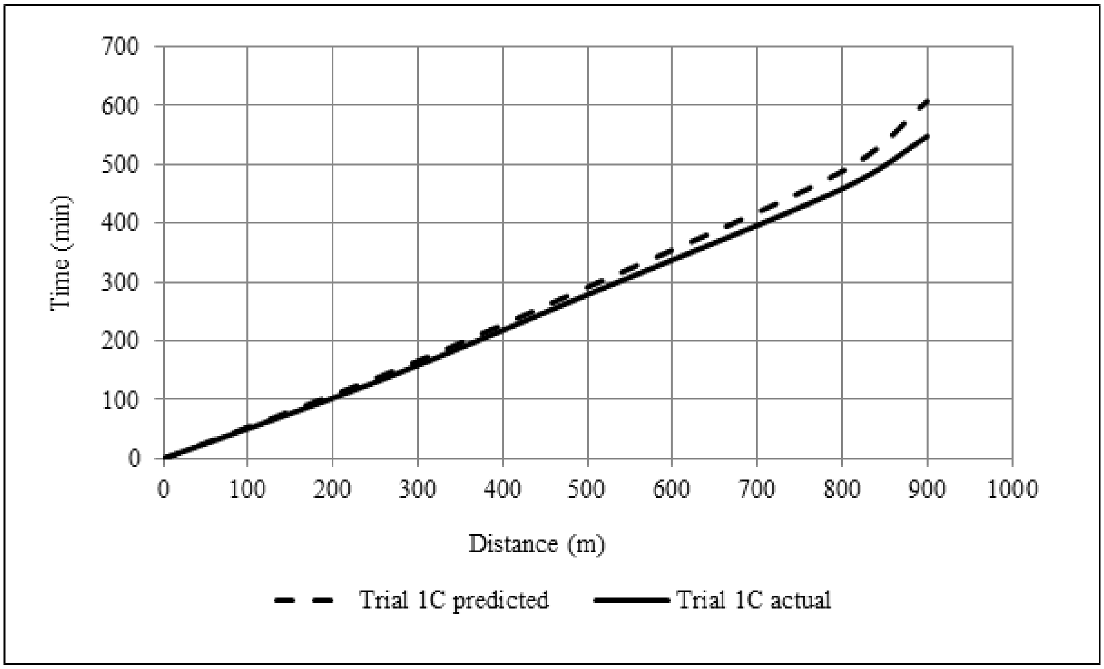


Figure 7.6: Actual and predicted advance curves - Trial 1C

The advance curves (Figures 7.6 - 7.8) closely mirror the cumulative infiltration curves (Figures 7.3 - 7.5). The actual and the scaled advance curves for Trial 1C (Figure 7.6) are close (apart from the downstream end of the field). The possible variance between the soil infiltration characteristics between the two halves of the field (as noted in Chapter 6) may have caused this small difference.

Figure 7.7 suggests that the advance never went past the halfway point, a prediction that was voided by the actual monitoring that was undertaken during that particular irrigation event (for the purpose of complete evaluation). The odd shape of the predicted advance curve is consistent with the predicted cumulative infiltration curve and performance for this particular trial discussed above.

The advance curve was successfully predicted for Trial 2D (Figure 7.8) in conformity with the predicted cumulative infiltration curves (Figure 7.5).

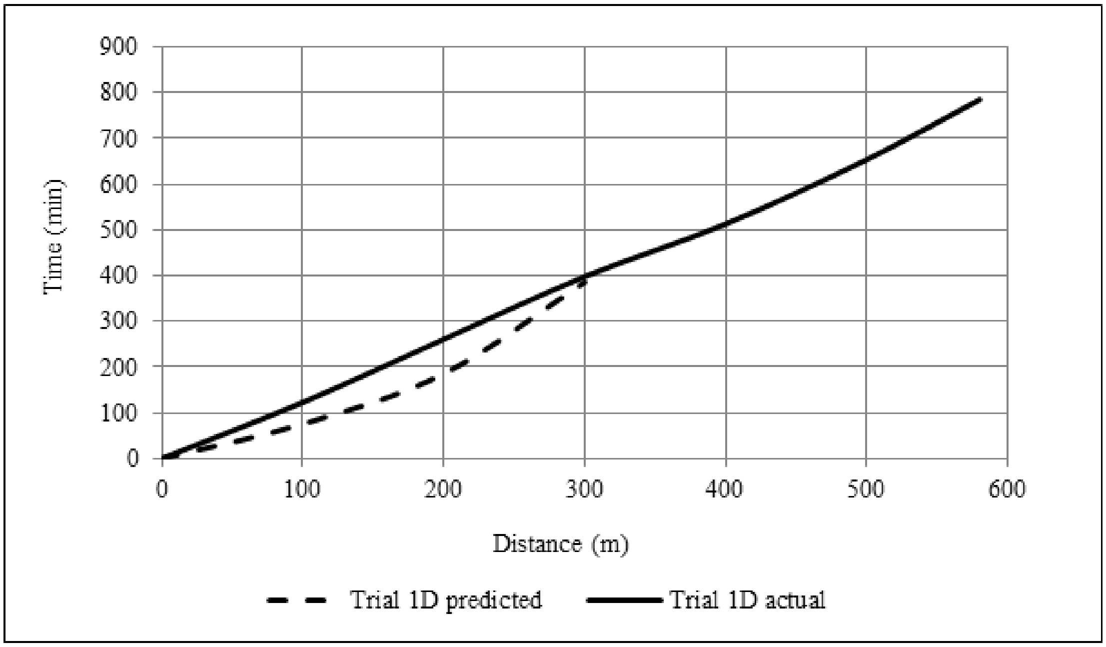


Figure 7.7: Actual and predicted advance curves - Trial 1D

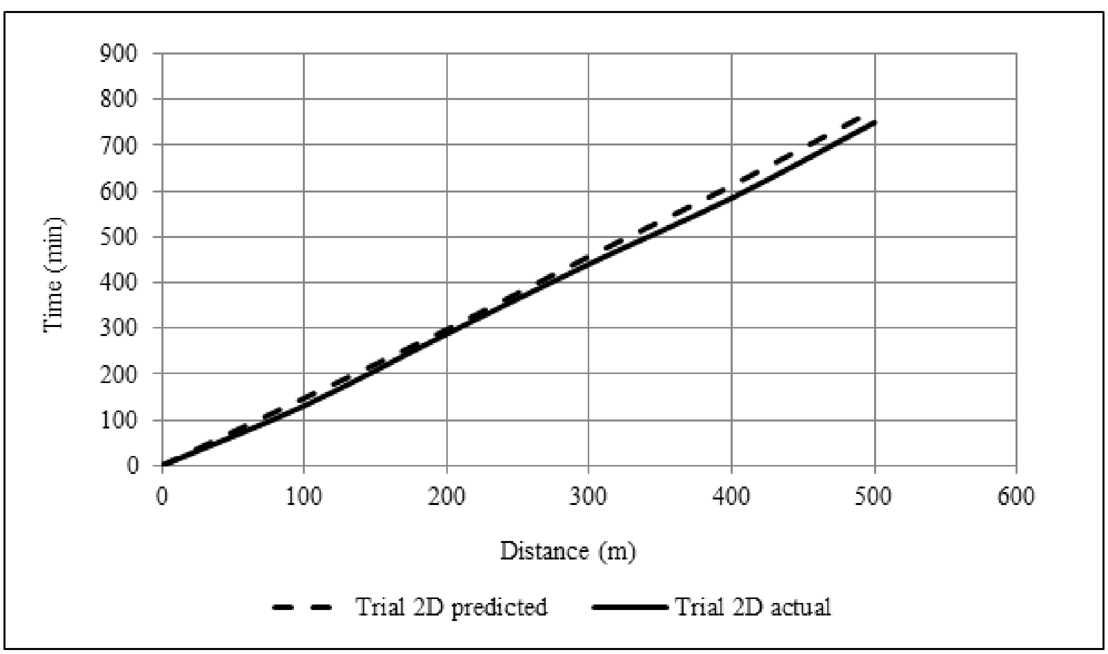


Figure 7.8: Actual and predicted advance curves - Trial 2D

7.5 Potential performance improvement

Tables 7.2 and 7.3 above suggest that there is $\leq$ 4% difference in the performance predicted and the actual irrigation (particularly AE and RE) in the case of Trials 1C and 2D. An investigation was carried out in this section to determine whether there were further potential gains in performance achievable as a result of adoption of alternative management strategies (particularly alternative objective function, the selection of advance distance used in the scaling process and the flow rate). The infiltration scaling, irrigation deficit and multi-furrow evaluation were exhaustively covered in the previous chapter and will thus not be revisited here.

7.5.1 Alternative objective function

The approach adopted here in the selection of an alternative objective function is similar to that used in section 6.2. That is, the evaluations involved maximising the AE subject to the threshold RE of $\geq$ 90%. However, since a similar alternative objective function was used in the 2011/12 field trials to test the optimisation system (Table 7.2), the new evaluations will focus on the data obtained from the complete evaluations (actual irrigations).

Evaluations on the actual irrigations (Table 7.4) suggested very minor (Trial 1C) and no change (Trial 2D) in AE with the new objective function. In both cases there was a small reduction in TCO. Conversely, there was an increase of 11% in the AE and a corresponding decrease of 166 minutes in TCO in the case of Trial 1D. This further confirms that the predictions given by the optimisation system for this particular trial (Table 7.2) could not have been accurate. The small difference between the best possible performance (AE) of the optimised and the actual irrigation (compared to the 2010/11 irrigation season trials) in the case of

Table 7.4: Actual irrigation and alternative objective function

Trial number	Actual irrigation (using actual infiltration)		Best possible performance using actual infiltration	
	AE (%)	TCO (min)	AE (%)	TCO (min)
1C	74	440	75	408
1D	77	798	88	632
2D	83	760	83	728

Trials 1C and 2D is an indication that the measures introduced in the present irrigation trials were beneficial.

7.5.2 Selection of the advance distance

Using 2011/12 field data from the three trials controlled using the optimisation system, simulations were undertaken using the SISCO model to determine the effect of advance distance used in scaling on: (i) scaling factor, (ii) predicted advance, and (iii) the irrigation performance. The evaluations used the same procedure as explained in section 6.7.

Plots of scaling factor versus advance distance is illustrated in Figure 7.9 (and the rest of the data tabulated in Appendix D.1). While scaling factors reduced with the increase in advance distances in the case of Trial 1D (as was demonstrated in Chapter 6), for Trials 1C and 2D the scaling factor appeared to remain relatively unchanged with the advance distance used in scaling. The shape of the cumulative advance curves of these trials trials (Figures 7.3 - 7.5) may provide an explanation for this difference. The predicted and actual cumulative infiltration curves for Trials 1C and 2D are relatively close. However, there was a significant difference in the case of Trial ID. In this case the scaled infiltration was on an upward trend (with the increasing advance distance) while there was only a small change in the actual predicted infiltration.

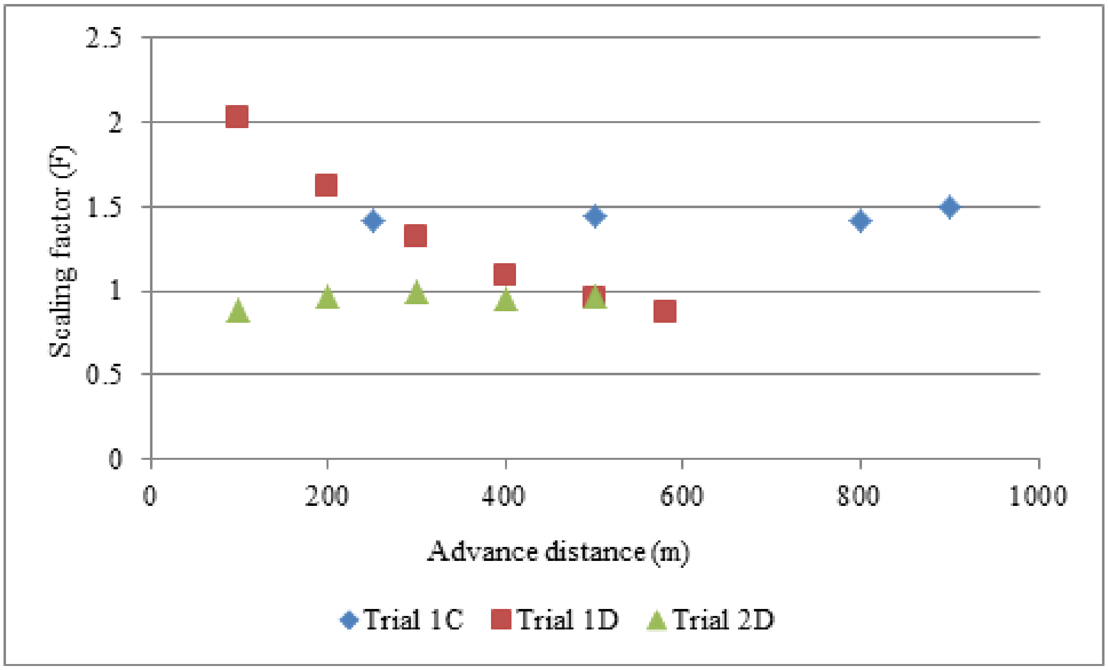


Figure 7.9: Effect of the advance distance on the scaling factor - Trials 1C, 1D and 2D

There was only minor differences (apparently in no particular order) in advance curves predicted at various advance distances for Trials 1C and 2D (Appendix D.1). The optimisation system had predicted (using advance distance of 300 m) that the advance only went to the half-way point (Figure 7.7) in the case of Trial 1D. However, simulations using advance distances > 300 m suggest the advance went beyond that point, although the prediction is still poor (Figure 7.10). Figure 7.10 demonstrates that moving the control point further down the furrow can compensate to some degree the effects of a poor model infiltration curve. Evaluations based on the 2010/11 irrigation season (Chapter 6) had suggested an overall improvement in advance prediction with the increase in the advance distance.

In terms of performance, Trial 1D suggested a rapid increase in the predicted AE (and reduced TCO) with the increase in advance distance (Table 7.5). There was also a decrease in inflow volume and drainage losses. However, for Trials 1C and 2D, performance appeared to vary in no particular order (Appendix D.1).

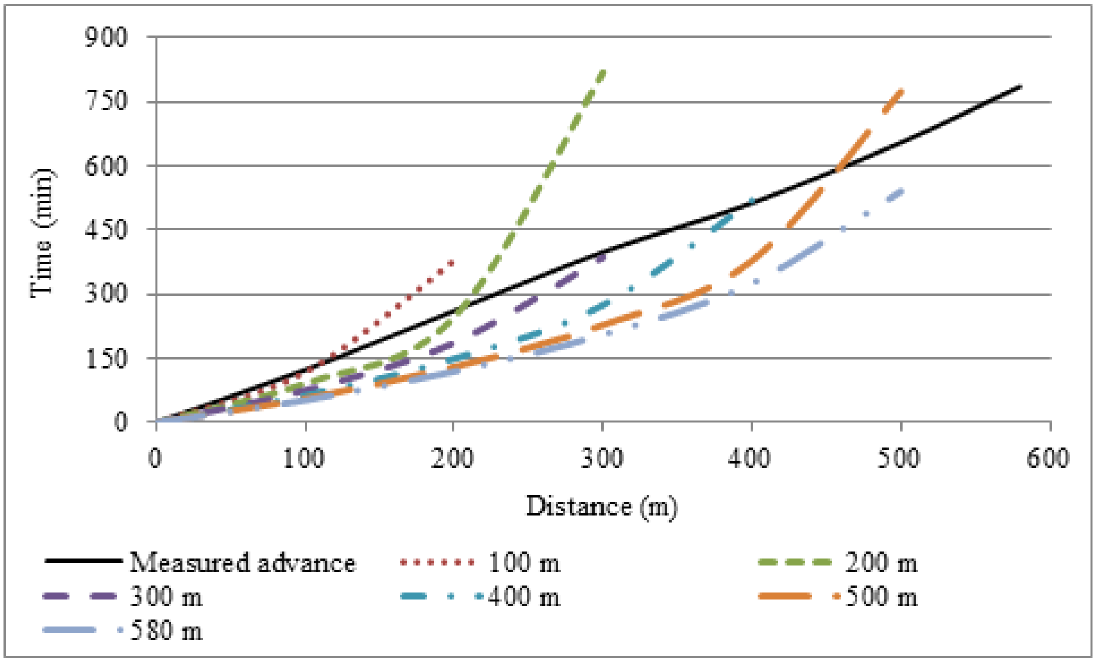


Figure 7.10: Effect of the advance distance on the predicted advance - Trial 1D

Table 7.5: Effect of advance distance on the performance of the optimisation system - Trial 1D

Optimisation strategy						
DU ≥						
RE ≥	61					
AE ≥						
	Advance distance (m)					
	100	200	300	400	500	580
Predicted Performance (%)						
AE			47	85	95	99
AE (with 90% recycling)			47	85	95	99
DU			0	0	0	5.6
RE			61	61	63	63
Inflow volume (m^3)			125	68	64	60
Drainage (%)			54	15	5	0
Runoff (%)			0	0	0	0
Time to cut off (min)			798	434	408	382

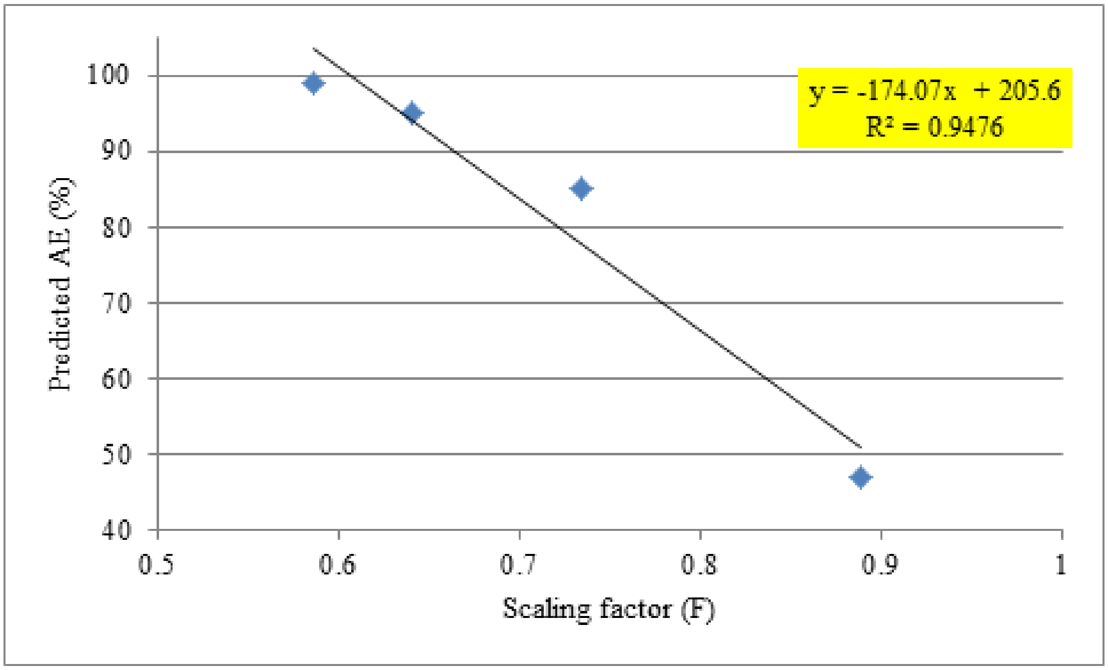


Figure 7.11: Scaling factor (F) versus predicted AE (%) - Trial 1D

The individual irrigations (Trials 1C, 1D and 2D) showed a strong negative correlation between the predicted AE and the scaling factor (R^2 >0.94). Trial 1D is given here as an example (the rest of the results are illustrated in Appendix D.1). These findings are consistent with the results obtained in 2010/11 irrigation season and discussed in section 6.7.

7.5.3 Varying the flow rate

In section 6.3 of Chapter 6, evaluations were undertaken to investigate the effect of varying the flow rate on AE, RE and RE for Trials 1A, 2A, 3A, 4A and 2B. A similar process was undertaken using the data obtained in the 2011/12 irrigation season. However, only one irrigation (Trial 2D) was selected for evaluation. This trial was selected on the basis of having the best (out of the three) irrigation performance (based on the AE). The SISCO hydrodynamic model was used in the evaluation.

As in section 6.3, flow rate was varied from between -75 to 100% while keeping all the other parameters constant (that is, TCO, field details, slope, furrow geometry and irrigation deficit). The scaled (Table 7.1) and the actual (Table 7.3) infiltration parameters were used in the SISCO model to evaluate the optimisation system and the actual irrigation respectively. The results are shown in Figure 7.12 and Appendix D.2.

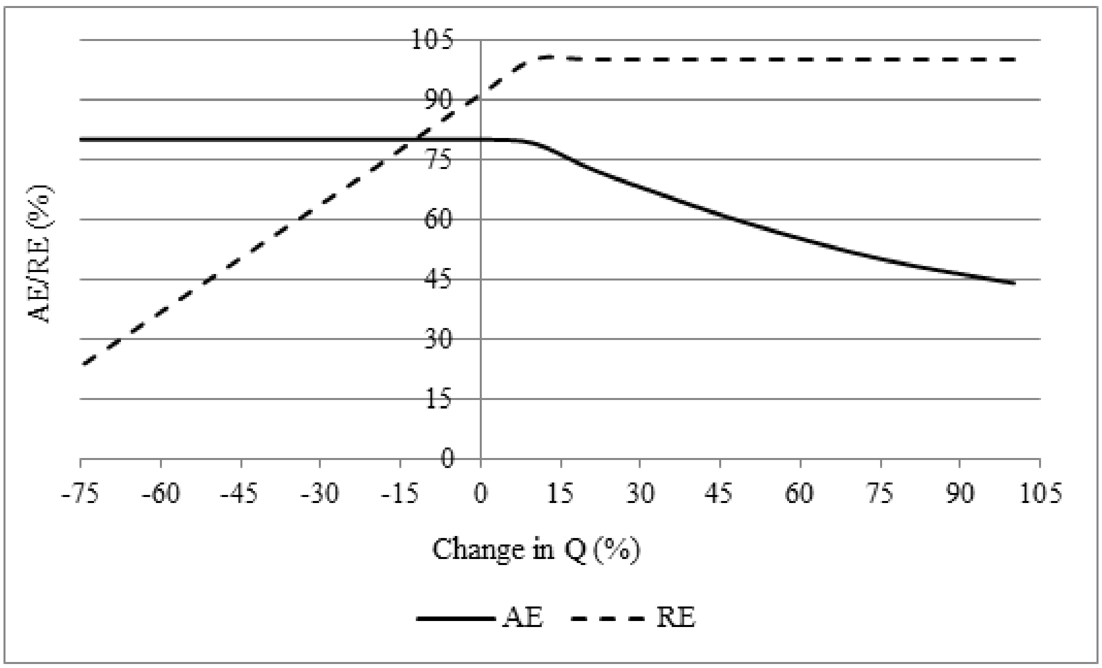


Figure 7.12: Effect of varying Q on AE and RE (optimisation system)

The results for both the optimisation system and the actual irrigations suggest that the reduction of flow rate had nil effect on the AE, however the RE reduced steadily. On the other hand, an increase flow rate caused the AE to reduce steadily, while the RE initially increased slightly before levelling off. The effect of varying the flow rate on both the AE and TCO (with RE of $\geq$90%) is illustrated in Figure 7.13 and Appendix D.2. A minimal increase in AE and a reduction in TCO is indicated.

Overall, these simulation results are similar to those relating to the optimisation system at Site A (discussed in section 6.3). Hence, the same conclusion will apply here: if an appropriate flow rate is selected to start with, any further change has minimal effect in improving the AE of the optimisation system. An appropriate flow rate can be selected during the initial evaluation (or from previous evaluations at the same site).

The importance of using an appropriate flow rate was demonstrated in section 6.3 with data obtained from Site B. The flow rate that was used (1.6 l/s) was too low, and hence the simulations undertaken suggested a significant increase in AE with an increase in inflow.

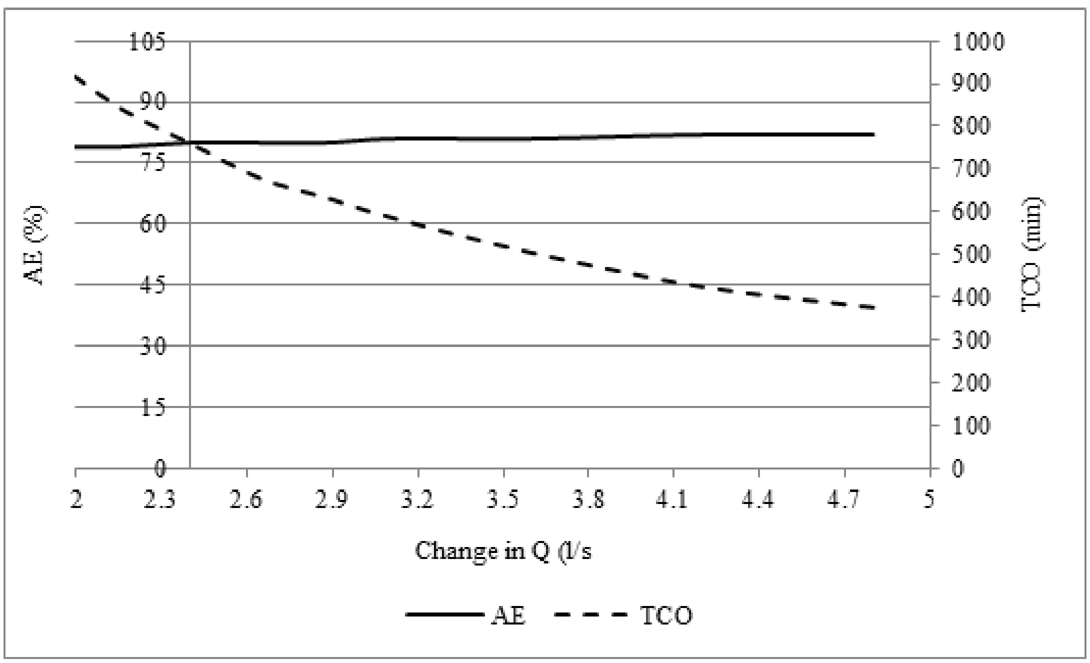


Figure 7.13: Effect of varying flow rate on AE and TCO (optimisation system)

The simulations involving variation of flow rates discussed in this chapter and the previous one are based on constant (steady) flow rates. The original intention in this research was to accommodate any variation in flow rates in the optimisation system. However, due to the technical problems encountered with the use of the PST to measure inflow, constant flow rates had to be assumed.

Anecdotal evidence suggest that under traditional irrigation management practices, furrow flow rates are hardly constant and thus it would be important to investigate the effect of any variation in flow rates on the optimisation system. Digital flow meters that can be used to measure varying flow rates are readily available in the market (as discussed in Chapter 2). This study could be extended to include deliberate variation in flow rates such as the 'cutback' flow regime discussed in subsection 2.7.2.

7.6 Conclusions

One trial in St George site and two in Dalby site were undertaken during the 2011/12 irrigation season. Selection of the model infiltration curve based on the average shape and the use of a simpler objective function in AutoFurrow (consisting only of AE and RE) are the changes effected following the analysis of results obtained from the 2010/11 trials.

The benefit of taking the average curve as the model curve was evident in the scaled and actual cumulative infiltration and advance curves for Trial 1C and 2D. In these trials the difference between the actual and scaled performance (AE and RE) was $\leq 4\%$. An assumed or 'guessed' model furrow was used for Trial 1D, and the result was a poor prediction of advance and cumulative infiltration.

It is concluded that an initial evaluation should be undertaken to determine the model infiltration curve prior to using the optimisation system in a field. Based on the evidence presented in this chapter, it is recommended that this be undertaken by averaging the shapes of all the infiltration curves obtained. During this evaluation the optimum flow rate for the site should also be determined. This is because it has been shown in this chapter that if an appropriate flow rate is selected to begin with, there can be no significant gain in the AE in any further changes. Further work is recommended to test the effect of variable and cutback flow regimes on the performance of the optimisation system.

Chapter 8

Conclusions and recommendations

8.1 Introduction

The overall aim of this research was to develop, prove and demonstrate a real time optimisation system for furrow irrigation. It had two hypotheses: (i) use of a real time optimisation system in furrow irrigation can lead to significant improvement in performance, and (ii) automated real-time control of furrow irrigation is feasible.

This final chapter presents the conclusions, recommendations and future research arising from this work. An overview of the previous chapters is initially provided to recap the significant trends in this PhD research before highlighting the conclusions about the research problem addressed. The main conclusions are then presented according to the objectives identified in Chapter 1. This is followed by the major outcomes of the research and finally opportunities for further research and other recommendations.

8.2 Overview of previous chapters

Chapter 1

A broad overview and background of the research theme and the irrigation industry in Australia in general was provided in this chapter. It was shown that although furrow irrigation is the dominant method for irrigation of irrigation of broad-acre such as cotton in Australia and the world, it has often been associated with low water use efficiency and high labour requirements. The chapter pointed out that efforts have been made over a number of years to address these shortcomings through automated optimisation and real time control. Although the on-going conversion of furrow (and broadly surface) irrigated lands to pressurised systems is expected to continue into the future, the furrow system is thought to remain important for years to come.

The research problem addressed throughout this dissertation (that is, designing a simple real time optimisation and control system for furrow irrigation) was outlined in this chapter, as well the key objectives. The potential outcomes and significance of this research were also identified.

Chapter 2

The major objective of this chapter was to review past work related to the research theme of this dissertation with a view of identifying the existing research gaps. Although this research focused on the furrow system, automation techniques used in other methods of surface irrigation (for example bay and basin) were reviewed because of their potential to be adapted for use by the former.

The review showed that initial attempts at improving the surface system focussed on reducing the labour requirements of the system through automation of the water delivery system. It was also shown that a wide range of surface irrigation automation hardware have since become widely available in Australia. The second phase of development of the surface system appeared to have combined automation with real time optimisation and control, and has often involved the use of computer simulation and hydraulic modelling.

The literature review revealed that although many of the methods proposed performed fairly well in research settings, none (to the best knowledge of the author) has been widely adopted by the irrigation community. Some of the reasons identified for this include complexities and high initial costs. Hence the chapter concludes that there is a strong case for the design of a simple, affordable and efficient automated furrow irrigation system utilising real time optimisation and control.

Chapter 3

In this chapter the furrow irrigation system utilising a real time optimisation and control process designed in this study was described. Soil infiltration characteristics are estimated in real time and the data used to control the same irrigation event to achieve optimum performance for the current soil conditions. The concepts of real time control and optimisation, and infiltration variability were covered in the chapter in some detail.

Chapter 3 described in depth the system developed and implemented for the purpose of the field trials. The system was designed by integrating a computer simulation model (AutoFurrow) with the associated automation hardware. The main components of the system are (i) a water delivery system, (ii) an inflow measurement system, (ii) a water sensor to monitor advance of water along the furrow, (iv) computing system, and (v) a radio telemetry system to facilitate communication among the system components.

The scaling technique was identified in this chapter as being the basis for the development of optimisation software (AutoFurrow). This implies the estimation of the soil infiltration characteristics based on a pre-selected model infiltration curve. AutoFurrow was developed using the SISCO simulation engine, which uses the full hydrodynamic model.

Chapter 4

This chapter outlined the methodology used in the evaluation of the system designed in Chapter 3. This was achieved by undertaking field trials over two consecutive irrigation seasons (2010/11 and 2011/12). A brief description of the field sites (St George and Dalby both in Queensland, Australia) including the soil and climatic conditions was provided in this chapter.

The chapter described both the field evaluations of the optimisation system as well as the complete evaluation of the system (similar to the conventional Irrimate^{TM} evaluation) including a multi-furrow based performance assessment. The description of the trials was broken down into the following components: (i) inflow measurement; (ii) advance monitoring; and (ii) telemetry system and hydraulic modelling. The challenges faced with the use of a PST during the 2010/11 irrigation season to measure pressure head (to be converted to flow rate) are described together with a potential solution.

Chapter 5

The results of the field trials undertaken in the 2010/11 irrigation season at St George were summarised in this chapter as follows: (i) model curves and the scaled infiltration parameters used in the real-time optimisation software (AutoFurrow) discussed in Chapter 3; (ii) irrigation performance predicted by the optimisation system; and (iii) complete irrigation performance evaluation comprising of one (model) furrow evaluation and performance expected as per the farmer's irrigation management practice

The optimisation trials as well as the complete evaluation were based on measured field variables (taken from the same trial furrow) and other model inputs. The normal management practice of the irrigator (mainly the TCO) was taken into account in determining the performance expected to be achieved by the irrigator. The standard irrigation performance measures (AE, DU and RE) were used in the analysis of the data.

This chapter also highlighted the error discovered in the software code after the completion of the trials and its effects on predicted: (i) TCO, (ii) irrigation performance, (iii) inflow volume, (iv) drainage, and (v) runoff. The post-irrigation re-simulation necessitated by the discovery of this error was explained in the chapter.

Chapter 6

Based on the field data described in Chapter 5, evaluations were undertaken in Chapter 6 to determine the effect (if any) of using alternative management strategies on the system performance. The following parameters were investigated: objective function, flow rate, irrigation deficit, infiltration scaling process, model curve, advance distance and multi-furrow evaluation.

Evaluations of the objective function involved setting RE at ≥90% and the SISCO model used to determine the best possible AE achievable both for the controlled trials and evaluations based on the actual infiltration. To evaluate the flow rate, flow rate was varied from -75% to 100% and the effect of this on AE and RE investigated using the SISCO model. With the same variance in flow rate, RE was set at ≥90% and the change in AE and TCO investigated. A similar investigation was undertaken with the irrigation deficit.

The effectiveness of the scaling procedure was evaluated by comparing the actual and the scaled curves. A novel method for selecting the model curve by determining the average curve from a group of curves was described in this chapter. A simple Excel-based program based on the equations shown in Chapter 6 was compiled to ease the generation of the model curve. Results from a multi-furrow evaluation, based on data collected during the complete evaluation process, is also summarised in the chapter.

Chapter 7

Chapter 7 summarised the results obtained from the 2011/12 irrigation season trials conducted at St George (Site C - the same cotton property used in the previous season) and Dalby (Site D). The same approach as described in Chapters 5 and 6 above was used in the evaluations of these data.

However, based on the previous results (2010/11 season), changes were made in the methodology of data acquisition as follows: (i) the Excel program described in Chapter 6 above was used to determine the model curve, (ii) a simple objective function consisting only of RE and AE was utilised, and (iii) a siphon flow meter and an ultrasonic flow meter were used for flow measurement (the PST was not used because of the challenges identified in Chapter 4).

8.3 Major conclusions from this research

As outlined in the introduction to this chapter (and also in Chapter 1), the research problem addressed throughout this dissertation was the design and demonstration of a simple real time optimisation and control system for furrow irrigation. The overall goal was to increase the water use efficiency and reduce the labour requirements of the most dominant method of irrigation in Australia and the world over. The two hypotheses successfully tested in this dissertation were: (i) use of real time optimisation and control in furrow irrigation can lead to significant improvement in irrigation performance, and (ii) automated real-time control of furrow irrigation is feasible. To test the hypotheses, the optimisation system involving an integration of pieces of hardware and software developed as part of this research (AutoFurrow) was designed. The system was subsequently tested in field trials in two consecutive irrigation seasons. The resultant data were analysed using the SISCO model. The major conclusions from this research are as follows:

- the real time optimisation and control system for furrow irrigation has the potential for improved irrigation performance and reduced labour costs;
- a simpler objective function (involving only RE and AE) would lead to a more robust optimisation process and still deliver improved performance;
- selection of the model infiltration curve can affect the optimisation system and an average curve used as the model would be more accurate; and
- the advance point chosen for control should be far enough down the furrow for best prediction yet still offer sufficient time to control the irrigation.

In summary, the first hypothesis has been supported fully by the field data and the subsequent analyses. The field trials also support the second hypothesis. Further evidence validating this hypothesis were obtained from the literature review undertaken in Chapter 2. The review showed that automation hardware are widely available in Australia and some techniques that have been used to automate other surface irrigation methods can be adapted to the furrow system. More importantly, the successful operation of the real-time optimisation system showed that real-time control is feasible.

Further evidence that support the hypotheses are discussed below in the context of the main objectives identified for this research in Chapter 1.

8.4 Major conclusions based on specific research objectives

Objective 1: *Evaluate alternative water delivery systems e.g. flexible fluming, bank-less channels, siphon and pipe through the bank (PTB)*
This objective was achieved by carrying out a desk stop study, an extensive literature review and laboratory experiments. The main purpose of this evaluation

was to assess the potential of these alternative water delivery systems to be used in automated furrow irrigation systems. The hydraulic laboratory experiments were conducted on gated Flexiflume (a type of layflat pipe widely used in the Australian irrigation industry) with the main objective of assessing the ability of this product to deliver high flow rates (about 6 l/s) at low heads. A full record of these hydraulic experiments is found in Appendix A.

The key conclusions for this objective are as follows:

- irrigation automation equipment are widely available in Australia;
- siphons are widely used for the irrigation of broad-acre row crops in Australia such as cotton, however their potential for automation appear to be technically infeasible;
- PTB are labour saving (compared to siphons) and can readily be automated in furrow systems;
- Flexiflume can be designed to supply high flow rates at low heads and distribute those flows evenly to furrows; and
- bankless channels offer the potential for significant labour saving and can be automated.

All the water delivery methods outlined above are currently used in furrow systems. Therefore their demonstrated potential for automation (apart from siphons) support the second hypothesis of this research (automated real-time control of furrow irrigation is feasible).

Objective 2: *Identify the appropriate numerical procedure to evaluate infiltration rates in real-time (while irrigation is underway)*
This research has concluded that SIRMOD, which is based on the full hydrodynamic model, is the most widely used simulation and optimisation tool for surface irrigation systems in Australia. Typically, historical infiltration data is

used in the model to modify future irrigations; the model is not normally applied for real time optimisation. However SIRMOD's potential for use as a 'quasi real time management tool' has been investigated by Hornbuckle et al. (2005). The model is often seen as data-intensive and is often used by skilled persons (mainly researchers and consultants).

It was concluded that the scaling model proposed by Khatri & Smith (2006) was appropriate because of its use of limited amount of data (for example only one advance point and the inflow rate). The model was applied in the new AutoFurrow software to perform the infiltration scaling.

The development of AutoFurrow software supports both hypotheses of this research. This is because of its potential to deliver improved irrigation performance and interface with automation hardware, thereby making automated real-time control of furrow irrigation feasible.

Objective 3: *Integrate modelling software with sensing, communication and control hardware*

To achieve the overall goal of this research, it was necessary to integrate modelling software and associated pieces of automation hardware. The AutoFurrow software was integrated with advance sensor, PST and telemetry system for the purpose of the field trials. Computer code in C and ASCII languages was written for this purpose. A computer was chosen as a controller because of the need for sufficient capacity to undertake robust hydraulic modelling.

It was concluded that the integration was successful as the optimisation system was able to automatically perform its intended functions (as expounded below) without user intervention. Some functions were undertaken manually in the field (e.g. turning the flow on and off), however the optimisation system can be made to work completely automatically if appropriate hardware are used.

The successful integration of software and hardware achieved in this research has made the automation of the furrow system feasible, and hence directly validates hypothesis 2. It also indirectly supports the first hypothesis because of its potential for performance improvement (as will be shown later).

Objective 4: *Prove the prototype system through appropriate field trials*
The optimisation system developed in this research was trialled at field sites in St George and Dalby over two irrigation seasons. Overall the system performed robustly and reliably, giving the preferred time to cut-off in adequate time for effective control of the irrigation events. The system was successful in delivering irrigation performance significantly better than that achieved by the grower. An error in the software code that was discovered after the first field trials was corrected in time for the final field trials.

The major conclusions drawn from the field tests on the optimisation system are:

- selection of the model infiltration curve is important and an incorrect curve may significantly limit the performance of the system;
- obtaining a model curve by averaging the shapes of all the curves from previous irrigations/evaluations resulted in more accurate scaled parameters than choosing a model curve at random;
- scaling using the hydrodynamic model was found to give a better prediction than scaling using the volume balance model;
- measuring flow rate through inference from pressure head measures using PST has practical difficulties and may be infeasible for a commercial system; and
- although selecting an advance distance which is beyond the midpoint may be preferable from the scaling point of view, it is important to allow sufficient time for the control of the irrigation event.

Objective 5: *Evaluate the benefits of adoption of the real time system*
Evaluation of benefits of adoption of the optimisation system in this research was limited to demonstrating performance improvements and labour savings aspects of the system. A complete economic analysis of the system was considered to be outside the scope of the research.

As explained above, the optimisation system performed robustly in the field without user intervention. Not all aspects of the system have been automated at the current stage of the project, meaning some operations for instance turning the flow on and off were achieved manually. Nonetheless, even with the level of automation during the field trials the potential for labour saving was demonstrated. The improved performance demonstrated by the system (compared to what the grower would have achieved) points to potential water savings.

Both the potential labour savings and performance improvement demonstrated in this research support both hypotheses 1 and 2.

8.5 Key outcomes

A functioning automated real time optimisation and control system for furrow irrigation is the major outcome of this research. This was the overall goal of this PhD study. Other significant outcomes, some related to the major project outcome are:

- the development of a unique software (AutoFurrow) for data acquisition, simulation, optimisation and control of furrow irrigation in real time;
- proof of the concept of real time optimisation and control of furrow irrigation through appropriate field trials;
- an Excel-based model for calculating an average curve (from a group of any number of curves) to be used as a model infiltration curve; and

- a detailed hydraulic study of flexible gated pipe and the validation and revision of GPIPE (software for analysis and design of gated irrigation pipes).

8.6 Recommendations for further research

It is anticipated that the new system for the optimisation and control of furrow irrigation will be adopted for commercial use in the future. The system seeks to be as efficient as the pressurised irrigation systems (in terms of labour, energy and water use efficiency), but less complex and significantly cheaper. This is expected to remove or reduce the need to 'migrate' to other systems which have been shown to be energy-intensive, potentially leading to higher greenhouse gas emissions and ultimately global warming. Of more immediate concern to farmers is the ever rising cost of energy. However, adoption of the system depends on development of a viable commercial system and a successful strategy for commercialisation.

As a consequence of this research, a number of areas identified for further research will now be outlined.

- A comprehensive economic analysis and quantification of savings from the application of the system. This will involve the development of a completely automated prototype of the system to be used for further testing and analysis.
- Commercial field scale trials to assist in the understanding of how the system may influence farm operations.
- Selection and further testing of appropriate hardware to be interfaced with the AutoFurrow software. As discussed earlier, a wide variety of hardware are commercially available in Australia.
- Extension of the system to bay irrigation. Bay irrigation, normally used for the irrigation of fodder crops differs from the furrow system in some

ways that might influence the real time optimisation system significantly. Bay systems are strategic because a significant number of them are already semi-automated and could offer a ready market for the new system.

- Development of a procedure to adjust the performance of the optimisation system (which is based on a model furrow) to reflect the true performance of the furrow set. Effectively this implies determining ways to introduce spatial variability into the optimisation process.

- Determination of the effect of using variable and cutback flow regimes on the performance of the optimisation system.

- Sensing for remote determination of the advance time. The current wire-based advance sensor is not ideal for a commercial system.

- Crop sensing and/or modelling to inform the automation process.

References

ABS (2008*a*), '2008 Year Book Australia, Number 90, Cat. no. 1301.0', Australian Bureau of Statistics, Canberra, Australia.

ABS (2008*b*), 'Water use on Australian farms, 2006-07, cat. no. 4618.0', Australian Bureau of Statistics, Canberra, Australia.

ABS (2010), 'Water use on Australian farms, 2008-2009, cat. no. 4618.0', Australian Bureau of Statistics, Canberra, Australia.

ABS (2011), 'Water use on Australian farms, 2009-10, cat. no. 4618.0', Australian Bureau of Statistics, Canberra, Australia.

Agbodo, E., Cape, J. & Willis, A. (1997), 'Performance testing of automatic irrigation equipment for surface irrigation', Technical Report, Australian Irrigation Technology Centre, South Australia.

Allen, R. G., Pereira, L. S., Raes, D. & Smith, M. (1998), 'Crop evapotranspiration - guidelines for computing crop water requirements', FAO Irrigation and drainage paper 56.

Armstrong, D. (2009), 'Modelling dairy farming systems', Technical Bulletin, Department of Primary Industries, Victoria.

ASABE (2008), 'Evaluation of irrigation furrows', ASAE EP 419.1, Feb 1993, ASABE.

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

AWMA (2009), 'Aquator automated irrigation', Catalogue, AWMA Pty Ltd.

Bautista, E., Clemmens, A. J., Strelkoff, T. S. & Schlegel, J. (2009), 'Modern analysis of surface irrigation systems with WinSRFR', *Agriculture Water Management* **96**, 1146–1154.

Bos, M. G. (1989), *Discharge measurement structures*, 3rd edn, ILRI Publication 20, International Institute for Land Reclamation and Improvement, The Netherlands.

Carter, M. & Grabham, M. (2008), 'Applying furrow irrigation water', WATERpak - a guide for irrigation management in cotton, Cotton Research and Development Corporation.

Christiansen, J. E. (1941), 'Hydraulics of sprinkler systems for irrigation', *Trans. ASCE* **107**, 221–250.

Christiansen, J. E. (1942), 'Irrigation by sprinkling', California Agricultural Experimental Station Bulletin 670, University of California, Davis.

Clemmens, A. J. (1992), 'Feedback control of basin irrigation system', *Irrigation and Drainage Engineering* **188**(3), 481–496.

Clemmens, A. J., Dedrick, A. R. & J., S. R. (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.

Dalton, P. & Raine, S. R. (1999), 'Measures of irrigation performance and water use efficiency. In research, development and extension in irrigation and water use efficiency: A review for the rural water use efficiency initiative.', National Centre for Engineering in Agriculture (NCEA), University of Southern Queensland, Toowoomba.

Dalton, P., Raine, S. R. & Broadfoot, K. (2001), 'Best management practices for maximising whole farm irrigation efficiency in the Australian cotton industry', Publication 179707/2, National Centre for Engineering in Agriculture (NCEA), University of Southern Queensland, Toowoomba.

Dassanayake, D., Dassanayake, K., Malano, H., Dunn, M., Douglas, P. & Langford, L. (2001), 'Water saving through smarter irrigation in Australian dairy farming: Use of intelligent irrigation controller and wireless sensor network', 18^{th} World IMACS/MODSIM Congress, Cairns, Australia, 13-17 July.

Doyle, P., Gibb, I. & Ho, C. (2009), 'Review of relevant information on potential productivity gains from on-farm irrigation technology', Report prepared for Dairy Australia by Murray-Darling Basin Inquiry.

Elliot, R. L. & Walker, W. R. (1982), 'Field evaluation of furrow infiltration advance functions', *Trans. of the ASABE* **25**, 396–400.

Emilio, C., Carlos, P. L., Jose, R. C. & Miguel, A. (1997), 'IPE: Model for management and control of furrow irrigation in real time', *Irrigation and Drainage Engineering* **123**(4), 264–269.

FAO (2003), 'AQUASTAT: Global information system on water and agriculture', Food and Agriculture Organisation, Rome, Italy.

Fisher, D. K. (2007), 'Automated collection of soil-moisture data with a low-cost microcontroller circuit', *Trans. of the ASABE* **23**(4), 493–500.

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

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

Gillies, M. H., Smith, R. J. & Raine, S. R. (2008a), 'Measurement and management of furrow irrigation at the field scale', Irrigation Australia National Conference and Exhibition, 20-22 May 2008, Melbourne.

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

Grabham, M. K., Hornbuckle, J. W., Raine, S. R. & Smith, R. J. (2008), 'Observations from initial evaluation trials of bankless channel irrigation systems', Irrigation Association of Australia National Conference, 20-22 May 2008, Melbourne.

Grabham, M. K., Hornbuckle, J. W., Raine, S. R. & Smith, R. J. (2009), 'Bankless channel irrigation systems: irrigation performance assessment', Irrigation Association of Australia National Conference, 18-21 October 2009, Swan Hill, Victoria.

Hibbs, R. A., James, L. G. & Cavalieri, R. P. (1992), 'A furrow irrigation automation system utilizing adaptive control', *Trans. of the ASABE* **35**(3), 1063–1067.

Hood, S. & Carrigan, E. (2006), 'Siphon-less irrigation systems: So how did they perform?', The Australian Cottongrower, DPI and F.

Hornbuckle, J., Christen, E. & Faulkner, R. (2005), 'Use of SIRMOD as a quasi real time surface irrigation decision support system', MODSIM 2005 Congress, 12-15 December 2005, Melbourne.

Hornbuckle, J. W., Car, N. J., Christen, E. W., Stein, T. M. & Williamson, B. (2009), 'IrriSatSMS - irrigation water management by satellite and SMS - A utilisation framework', CSIRO Land and Water Science Report No. 04/09.

Humpherys, A. S. (1971), 'Automation of furrow irrigation systems', *Trans. of the ASABE* **14**(3), 460–470.

Humpherys, A. S. (1995a), 'Semi-automation of irrigated basins and borders: I. single function turnout gates', *Trans. of the ASABE* **2**(1), 67–74.

Humpherys, A. S. (1995b), 'Semi-automation of irrigated basins and borders: II. dual-function turnout gates', *Trans. of the ASABE* **2**(1), 75–82.

Humpherys, A. S. (1995c), 'Semi-automation of irrigated basins and borders: III. control elements and system operation', *Trans. of the ASABE* **11**(1), 83–91.

Humpherys, A. S. & Fisher, H. D. (1995), 'Water sensor feedback control system for surface irrigation', *Trans. of the ASABE* **2**(1), 61–65.

Humpherys, A. S. & Lauritzen, C. W. (1962), 'Shape factors for hydraulic design of layflat irrigation tubing', *Trans. of the ASABE* **5**, 175–179.

Humpherys, A. S. & Lauritzen, C. W. (1964), 'Hydraulic and geometrical relationships of lay-flat irrigation tubing', U.S. Department of Agriculture, Technical Bulletin No.1309.

Kemper, W. D., Trout, T. J. & Kincaid, D. C. (1987), *Cablegation: Automated supply for surface irrigation*, In: Advances in irrigation, Academic Press Inc., London, pp. 1–66.

Khatri, K. L. (2007), 'Toward real-time control of surface irrigation', PhD Thesis, University of Southern Queensland, Toowoomba.

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.

Khatri, K. L. & Smith, R. J. (2007), 'Toward a simple real-time control system for efficient management of furrow irrigation', *Irrigation and Drainage* **56**(4), 463–475.

Kincaid, D. C. & Kemper, W. D. (1982), 'Cablegation: II. Simulation and Design of the Moving-Plug Gated Pipe Irrigation System', *Trans. of the ASABE* **25**(2), 388–395.

Lam, Y. S., Wallender, D. C. & Upadhyaya, S. K. (2007), 'Machine vision monitoring for control of water advance in furrow irrigation', *Trans. of the ASABE* **50**(2), 1162–1170.

Langat, P. K., Smith, R. J. & Raine, S. R. (2008), 'Estimating the furrow infiltration characteristic from a single advance point', *Irrigation Science* **26**, 367–374.

Latimer, E. A. & Reddell, D. L. (1990), 'Components of an advance rate feedback irrigation system (ARFIS)', *Trans. of the ASABE* **33**(4), 1162–1170.

Lavis, A., Maskey, R. & Lawler, D. (2007), 'Quantification of farm water savings with automation', Department of Primary Industries, Victoria.

Leonardi, S. & Roth, S. (2008), 'Irrigation in Australia. Facts and figures', National Program for sustainable irrigation (NPSI).

Mailhol, J. C. & Gonzalez, J. M. (1993), 'Furrow irrigation model for real-time applications on cracking soils', *Irrigation and Drainage Engineering* **119**(5), 768–783.

Maskey, R., Roberts, G. & Graetz, B. (2001), 'Farmers attitudes to the benefits and barriers of adopting automation for surface irrigation on dairy farms in Australia', *Irrigation and Drainage Systems* **15**, 39–51.

McCarthy, C. L. (2004), 'Advance rate measurement for furrow irrigation', PhD Thesis, University of Southern Queensland.

McCarthy, C. L., Symes, T., Rees, S. J., Kamel, P., McHugh, A. D., Eberhard, J. & McKeering, L. M. (2008), 'PIMS manual', National Centre for Engineering in Agriculture (NCEA), University of Southern Queensland, Toowoomba, Publication 1002008/5.

McClymont, D. J. (2007), 'Development of a decision support system for furrow and border irrigation', PhD Thesis, University of Southern Queensland, Toowoomba.

McClymont, D. J. & Smith, R. J. (1996), 'Infiltration parameters from optimisation on furrow irrigation advance data', *Irrigation Science* **17**(1), 15–22.

McClymont, D. J., Smith, R. J. & 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.

McNown, J. S. (1954), 'Mechanics of manifold flow', *Trans. of the ASCE* **119**, 1103–1118.

Molden, D. (2007), *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*, Earthscan and International Water Management Institute, London and Colombo, London and Colombo.

Mostafazadeh-Fard, B., Osroosh, Y. & Eslamian, S. (2006), 'Development and evaluation of an automatic surge flow irrigation system', *Agriculture and Social Sciences* **2**(3), 129–132.

Niblack, M. & Sanchez, C. A. (2008), 'Automation of surface irrigation by cut-off time or cut-off distance control', *Trans. of the ASABE* **24**(5), 611–614.

Plusquellec, H. (2009), 'Modernization of large-scale irrigation systems: is it an achievable objective or a lost cause?', *Irrigation and Drainage* **58**, 104–120.

Purcell, J. (1994), 'Siphon and culvert hydraulics', Surface irrigation: a guide for farm managers, Irrigation Association of Australia.

Raine, S. R. (2006), 'The future of irrigation technologies and practices is here now', Keynote address, Irrigation Australia 2006 Conference, 9-11 May, Brisbane, p26-30.

Raine, S. R. & Foley, J. P. (2002), 'Comparing application systems for cotton irrigation - what are the pros and cons?', Field to fashion, 11^{th} Australian Cotton Conference, Australian Cotton Growers Research Association Inc.

Raine, S. R., McClymont, D. J. & Smith, R. J. (1997), 'The development of guidelines for surface irrigation in areas with variable irrigation', Proceedings of the Australian Society of Sugar Cane Technologists, Townsville, p293-301.

Raine, S. R. & Shannon, E. L. (1996), 'Improving the efficiency and profitability of furrow irrigation for sugarcane production', CSIRO Division of Tropical Crops and Pastures, Brisbane.

Raine, S. R. & Smith, R. J. (2007), 'Simulation modelling for surface irrigation evaluation: Training in using SIRMOD and IPARM', National Centre for Engineering in Agriculture (NCEA), University of Southern Queensland, Publication 1000008/5.

RUBICON (2011), 'Rubicon Water: NVIRP Project Technology', Catalogue, RUBICON Water.

Scaloppi, E. J. (1988), 'Adjusted 'F' factor for multiple-outlet pipes', *Irrigation and Drainage Engineering* **114**(1), 169–174.

Smith, M. & Nayar, M. (2008), 'The first stage of Coleambally Water Smart Australia Project: Building on CICL's adoption of Total Channel Control (TCC)', Irrigation Australia National Conference and Exhibition, 20-22 May 2008, Melbourne.

Smith, R. J. (1988), 'Energy loss in branching flow and its application to irrigation pipeline design', *Agricultural Engineering Research* **41**, 181–189.

Smith, R. J. (1990), 'The distribution of water from rigid and layflat gated pipes', Proceedings of Australian Society of Sugar Cane Technologists, 1990 Conference, Townsville, p56-64.

Smith, R. J. & Gillies, M. H. (2010), 'Head ditch hydraulics and the variability of inflows to irrigation furrows', *Irrigation and Drainage* **59**(4), 442–452.

Smith, R. J., Gillies, M. H., Shanahan, M., Campbell, B. & Williamson, B. (2009), 'Evaluating the performance of bay irrigation in the gmid', Irrigation

Association of Australia National Conference, 18-21 October 2009, Swan Hill, Victoria.

Smith, R. J., Raine, S. R., McCarthy, A. & Hancock, N. (2007), 'Managing spatial and temporal variability in irrigated agriculture through adaptive control', Society for Engineering in Agriculture National Conference, 23-26 September 2007, Adelaide.

Smith, R. J., Raine, S. R. & Minkevich, J. (2005), 'Irrigation application efficiency and deep drainage potential under surface irrigated cotton', *Agricultural Water Management* **71**, 117–130.

Smith, R. J., Watts, P. J. & Mulder, S. J. (1986), 'Analysis and design of gated irrigation pipelines', *Agricultural Water Management* **12**, 99–115.

SPACEPAC (2010), 'Overbank siphons', Catalogue, SPACEPAC Pty Ltd.

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.

Strelkoff, T. S., Clemmens, A. J., Schmidt, B. V. & Slosky, E. J. (1996), 'BORDER - a design and management aid for sloping border irrigation systems', US Department of Agriculture, Agricultural Research Service, WCL Report 21.

Trout, T. J. (1990), 'Furrow inflow and infiltration variability impacts on irrigation management', *Trans. of the ASABE* **33**(4), 1171–1178.

Trout, T. J. & Mackey, B. E. (1988), 'Furrow flow measurement accuracy', *Irrigation and Drainage Engineering* **114**(2), 244–255.

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.

USDA-ALARC (2009), 'Surface irrigation analysis, design and simulation', WinSRFR 3.1 Help and Manual, US Department of Agriculture, Agricultural Research Service, Arid-Land Agricultural Research Centre.

Walker, W. R. (1989), 'Guidelines for designing and evaluating surface irrigation systems', FAO Irrigation Drainage Paper 45.

Walker, W. R. (1997), *SIRMOD II - Irrigation simulation software*, Utah State University, Logan.

Walker, W. R. & Skogerboe, G. V. (1987), *Surface irrigation: Theory and Practice*, Prentice-Hall, New York.

Wigginton, D. (2008), 'Theoretical flow rates for siphons: head discharge charts', WATERpak - a guide for irrigation management in cotton, Cotton Research and Development Corporation.

Wood, M. & Martin, M. (2000), 'Improved irrigation practices for forage production: Module 2. Alternative irrigation technology desktop analysis', Final Report, Department of Natural Resources and Environment, Tatura, Victoria.

Appendix A

Hydraulics of large diameter gated flexible fluming

The initial plan in this research project was to use a large diameter gated flexible (or layflat) to deliver water to furrows. Consequently, hydraulic experiments involving two sizes of layflat were undertaken in the Hydraulics laboratory at USQ. The results of this work are summarised in this appendix. Some parts of the work have been used in Chapters 2 and 3.

Abstract

Gated flexible or layflat fluming is used in furrow irrigation to supply water to individual furrows. Due to limited published data on the hydraulic design of gated layflat, laboratory experiments were conducted to establish the flow characteristics of these pipes under the low heads and high flow rates typical of furrow irrigation of cotton in Australia.

Two different diameters of layflat were used in the study, 222.8 and 425 mm. Proprietary 50 mm diameter outlets (gates) were installed in the layflat at 1 m spacings. Trials were conducted at various pressures and flow rates to determine: the geometric characteristics of the fluming and their relationship to pressure, the friction loss coefficient for the fluming with and without the outlets installed, and the head-discharge characteristic for the outlets.

It was shown that the fluming is capable of supplying the desired flow rates (about 6 l/s per furrow) at pressure heads of less than 1 m. The head-discharge characteristic for the proprietary outlets followed a similar form to the standard orifice equation. No evidence was found to suggest that the velocity head played any significant role in determining the outlet discharge.

The Hazen-Williams coefficient, C_{HW}, of the fluming with the outlets installed was a low 80 compared to a value of about 140 for the fluming without gates, illustrating the increase in pipe friction caused by the protrusion of the gates into the flow. These experimentally derived coefficients and characteristic equations were used to validate the simulation program GPIPE developed previously for the design and analysis of rigid gated pipe systems. This produced a good correlation between the measured and simulated discharge and pressure profiles, confirming the applicability of the GPIPE program in the hydraulic design of layflat gated pipes.

INTRODUCTION

Flexible fluming or layflat is a pipe whose cross-sectional area varies according to the fluid pressure being transmitted. The pipe lays flat when empty, and approaches fully round shape as the fluid pressure inside the pipe increases. Some of the materials that have been used to make layflat are polyethylene, canvas, vinyl and butyl. Flexible fluming is used both for conveyance and distribution of water to furrow irrigated crops. In the latter case, outlets or gates are installed (according to the furrow spacing) along the length of the fluming to supply water to individual furrows. The use of gated layflat in furrow irrigation is convenient for machinery operations as it removes the need for head ditches. It is also relatively low-cost, easily transportable and requires little storage space. In Australia layflat is widely used in the sugar industry, but so far has not been successfully applied in the cotton industry because of the higher flow rates ($\sim$ 6 l/s) required for the longer furrows ($\sim$ 1000 m) used in that industry (Smith and Gillies 2009).

The layflat fluming used predominately in Australia is known by the trade name ‘Flexiflume’. It is made of woven polyethylene with a wall thickness of about 2 mm. It employs proprietary outlets, made of PVC and polyethylene, which consist of a circular ‘Ogee’ shaped valve seat with a 50 mm diameter throat and a removable and adjustable valve/deflector/insert (Figure A.1). The mouth of the valve seat extends approximately 25 mm into the pipe while the outer part houses the adjustable valve screws into the valve seat. It is used to adjust the outlet discharge but can be removed altogether if a higher flow rate is desired. The adjustable valve is also designed to deflect and disperse the water stream to minimise soil erosion in irrigation furrows.

In this study, hydraulic experiments were conducted on gated Flexiflume of internal diameters 222.8 and 425 mm. The objectives of the study were to: (i) assess the ability of this product to deliver high flow rates at low heads; (ii) assess the uniformity of outlet flows at these high flow rates; (iii) develop a head discharge

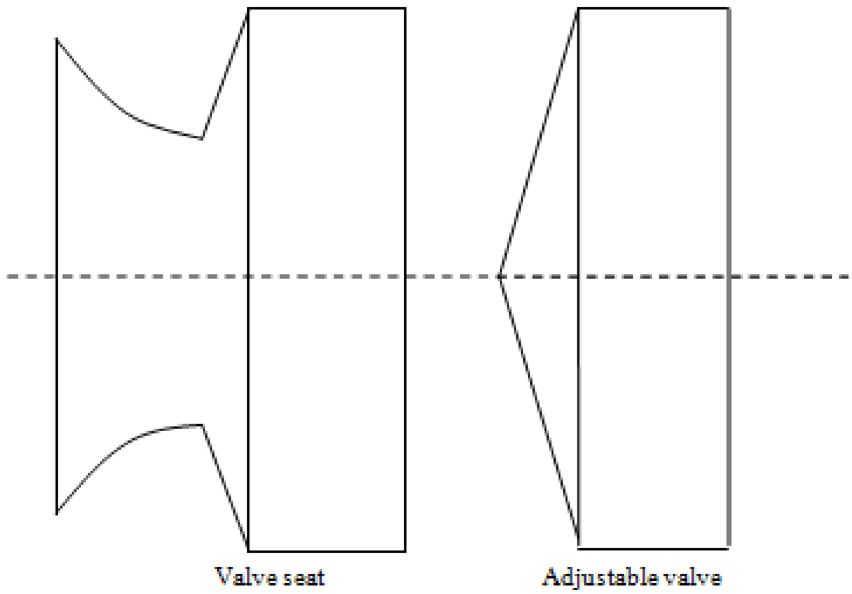


Figure A.1: Flexiflume outlet

characteristic equation describing the outflows through the plastic outlets supplied with the fluming; and (iv) provide data for the validation of the simulation program GPIPE developed by Smith (1990) for the design of gated pipe systems.

HYDRAULICS OF FLEXIBLE FLUMING

There is limited published literature on the hydraulics of layflat irrigation tubing, the notable study being that of Humpherys and Lauritzen (1962 and 1964). They showed that at high pressures when the pipe is circular, layflat can be designed or analysed using the conventional equations relating energy losses with flow velocity such as the Darcy-Weisbach and Hazen-Williams equations. However, unlike rigid irrigation pipes, the shape and cross-sectional area of layflat irrigation tubing at normal operating pressures is dependent upon the fluid pressure. At the relatively low pressures normally used in gated fluming, the cross section adopts an oval shape flattened at the bottom where the pipe rests on the ground surface. The effect is to decrease the cross-sectional area of the flow and hence increase the hydraulic radius and rate of friction loss compared to that of the equivalent circular section.

Humpherys and Lauritzen (1962 and 1964) proposed a method to predict the friction loss in flexible non-circular fluming. They suggested that the friction loss is equal to that in a circular pipe of the same diameter and roughness multiplied by a factor β_f where:

$$\beta_f = \beta \left(\frac{A}{a} \right)^{m+n} \tag{A.1}$$

where β is a shape factor, A is the cross-sectional area of the conduit when fully circular, a is the cross-sectional area (non-circular) at the particular pressure, m is the exponent on the discharge or velocity term in the flow equation being applied, and n is the exponent on the diameter or hydraulic radius term. In the case of the Darcy-Weisbach equation $m = 2$ and $n = 1$, while for Hazen-Williams $m = 1.852$ and $n = 1.167$.

The modified Darcy-Weisbach equation for uniform flow thus becomes:

$$h_f = \beta_f \frac{\lambda L {V_v}^2}{2gD} \tag{A.2}$$

where h_f is the friction loss, λ is the friction factor for the equivalent circular pipe, L is the length of the pipe, V_v is the mean velocity of flow in the equivalent circular pipe, D is the diameter of the equivalent circular pipe, and g is the gravitational constant.

According to Humpherys and Lauritzen the factor β_f is constant for a given pipe shape and they also provided data in graphical form relating β_f to the height-width (d/w) and pressure head-diameter (H_p/D) ratios. To make this data more accessible, Smith (1990) fitted a curve to the data resulting in the equation:

$$\beta_f = \beta \left(\frac{A}{a}\right)^3 = \frac{H_p}{(1.07H_p - 0.409D)} \tag{A.3}$$

Further, Humpherys & Lauritzen (1964) provided a graphical relationship (see Figure A.3) between the head-diameter (H_p/D), height-width (d/w) and area (a/A) ratios which can be used to determine the cross-sectional area of the pipe for any diameter and pressure.

The flow in gated pipe (rigid or layflat) is spatially varied, decreasing approximately uniformly to zero at the downstream end. Hence the rate of frictional losses also decreases along the length of the pipe, decreasing to zero at the closed end. Smith et al. (1986) provided a comprehensive description of the hydraulics of gated pipelines and for the system they analysed concluded that for the theory to match the experimental results:

- there must be no or negligible energy loss in the flow continuing past each gate or outlet apart from the usual pipe friction losses, and
- the velocity head was equal to $1.1V^2/2g$.

The outlets or gates in gated pipe are essentially orifices and any expression characterising their outflows would be expected to follow the standard orifice equation:

$$Q_o = C_d A_o \sqrt{2gH_p} \tag{A.4}$$

where Q_o is the outlet discharge, C_d is a coefficient of discharge, and A_o is the area of gate.

Smith et al. (1986) also showed that, for the particular outlets used in their study, the gate outflow was also a function of the velocity head (H_v) in the pipeline immediately upstream of the outlet, the velocity head serving to reduce the discharge from that predicted by the simple orifice equation. They developed the following empirical equation:

$$Q_o{}^2 = A_o{}^2(8.38H_p - 1.24H_v) \tag{A.5}$$

This result supported earlier work of Kincaid & Kemper (1982) who also observed this velocity head influence. More recently, Smith (1988) drew on the analysis of manifold flow by McNown (1954) to produce an exact theoretical model for the prediction of the gate outflows in the absence of a specific empirical gate characteristic.

The work of Smith et al. (1986) and Smith (1988) culminated in the development of the computer program GPIPE for the design and analysis of rigid and flexible gated pipe (Smith 1990). This program applies the continuity and energy equations in a step-by-step process starting from the downstream or closed end. Pipe friction losses are described by the Hazen-Williams equation and include the modification for flexible pipelines from Humpherys & Lauritzen (1962) as encapsulated in Eqn A.4 above. A specific user defined outlet characteristic can be employed or the theoretical model of Smith (1988).

EXPERIMENTAL METHODOLOGY

The tests were conducted in the Hydraulics Laboratory at the University of Southern Queensland and involved two layflat pipes of inside diameters 425 mm and 222.8 mm, each 12 m long. Tests were designed to determine the shape characteristics of the fluming, the friction characteristics with and without outlets installed, and the outlet characteristic equation for the particular outlets with and without the adjustable valve installed.

Water used for the experiments was drawn from an elevated constant head tank. A butterfly valve was used to control pressure and total flow from the elevated tank into the layflat. An ultrasonic flow meter mounted on a horizontal section of the PVC supply pipe was used to measure the discharge into the layflat. All testing was done with the layflat level on the floor of the laboratory. Ambient air and water temperatures were about 15 °C throughout the tests.

The hydraulic grade line or potential energy (elevation plus pressure) was measured using a bank of 10 manometers, with tapping points at 1 m spacings, immediately upstream of the outlet locations. The outlet discharges were measured using a collection bin and an electromagnetic flow meter (Figure A.2). The total inflow and the height and width of the layflat were also measured.

Figure A.2: Bin and flow meter for outflow measurement

Friction tests were conducted on the 222.8 mm layflat (before the outlets were installed) at various constant flow rates ranging from 6 to 46 l/s to determine the underlying friction coefficient for the particular pipe material. The downstream end was open and elevated slightly to ensure a pressure that could be measured on the manometers.

For the remainder of the trials, outlets were installed in the fluming at 1 m spacings. The purpose of the tests undertaken with the gates installed was multi-faceted. They provided data for determination of a head-discharge characteristic equation for the gates, to characterise the additional friction losses caused by protrusion of the gates into the flow, and for the validation of the GPIPE model.

For these tests the downstream end of the layflat was closed by tightly clamping the pipe about 1 m downstream of the last outlet. The trials undertaken and the ranges of total discharge and average pressure for the two pipes are summarised in Table A.1. The tests were performed both with the adjustable valves installed (and adjusted to fully open position) and with the valves removed. The maximum pressure in the pipe was kept below the maximum working pressure recommended by the manufacturer (that is, 5 and 1.4 m for the 222.8 and 425 mm diameter pipes, respectively). High pressures were also avoided to avoid unnecessary breakup of the flow streams and hence incomplete capture of the stream in the measuring bin.

Table A.1: Summary of outflow and pressure trials

	222.8 mm Φ pipe		425 mm Φ pipe	
Total flow rate (l/s)	25.8-43.7	20.6-26.0[a]	40.8-59.5	16.5-25.6
Average pressure[b] (mm)	137-520	462-638	270-599	458-1065
Number of trials	8	2	3	4

[a] For some trials between 1 and 5 outlets were sealed off to allow higher outlet flow rates
[b] The pressure was measured relative to the centre of the outlet

RESULTS AND DISCUSSION

Layflat geometry

Humpherys & Lauritzen (1962) showed that the relationship between pressure and cross-sectional shape of the layflat is important in describing the hydraulic behaviour of these flexible pipelines. A plot of head-diameter (H_p/D) and height-width (d/w) ratios measured for the 222.8 mm diameter layflat (Figure A.3) returned a curve similar to that of Humpherys & Lauritzen (1964). This confirms that the behaviour of the layflat is sufficiently similar to the product they tested to allow application of their geometrical relationships and friction loss correction to the layflat. These relationships are used in the subsequent analyses.

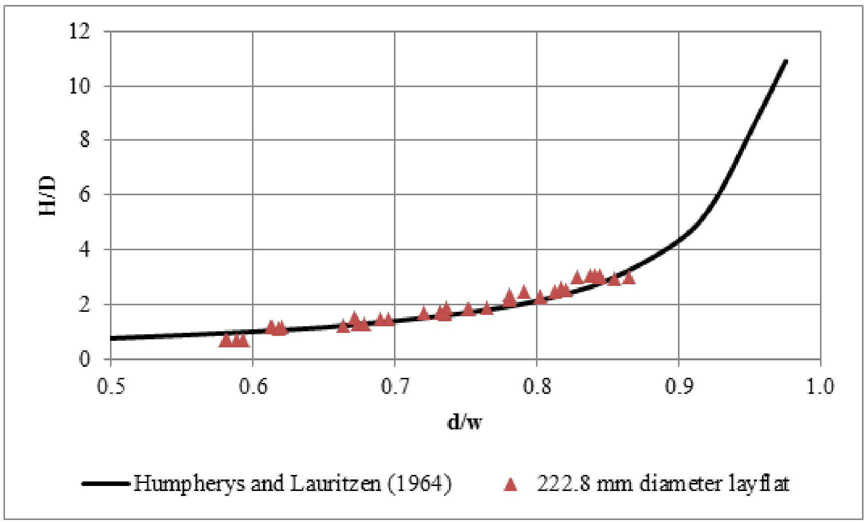


Figure A.3: Relationship between the head-diameter and height-width ratios for the layflat superimposed over the curve provided by Humpherys and Lauritzen (1964)

Pipe friction (without outlets)

The results of the pipe friction trials are given in Table A.2. The friction slope was taken directly from the manometer readings. To account for the non-circular shape of the layflat in the calculation of flow velocity, the cross-sectional area of the layflat for each trial was determined from the measured height/width ratio (d/w), by using the graphical relationship from Humpherys & Lauritzen (1964). Equation A.3 was used to calculate the friction correction factor and the Hazen-

Williams coefficient was calculated from rearrangement of:

$$V = 0.849C_{HW}\left(\frac{D}{4}\right)^{0.63}\left(\frac{h_f}{L\beta_f}\right)^{0.54} \tag{A.6}$$

The analysis returned values for the Hazen-Williams coefficient ranging from 62 to 148 (Table A.2). Ignoring the two low values at the very low flow rates (well below those used in the field), these values are not inconsistent with the manufacturer's recommended C_{HW} for the layflat tested (Flexiflume) of 145.

Table A.2: Determination of C_{HW}

Test	Discharge (l/s)	Friction slope h_f/L (mm)	β_f	Velocity (m/s)	C_{HW}
1	6.12	0.000739	1.150	0.160	62
2	14.15	0.001818	1.039	0.366	82
3	19.70	0.001527	1.016	0.509	124
4	23.60	0.003073	1.004	0.609	101
5	32.00	0.002679	1.009	0.826	148
6	41.10	0.006352	1.145	1.074	129
7	46.90	0.009085	1.093	1.219	118
8	46.30	0.009364	1.097	1.204	115

The cross-sectional area of the layflat is expected to slightly reduce towards the downstream end of the layflat as the pressure decreases. But because only relatively short lengths of these pipes are normally used as gated irrigation pipelines, this effect was ignored in the study.

Pressure head variation

In general the pressure head (upstream of each gate) increased slightly towards the closed end of the layflat, with the increase being more obvious in the smaller diameter pipe and at the higher flow rates with the adjustable valves removed (Figure A.4). This can be attributed to the pressure head recovery that occurs as the flow passes each outlet (Smith et al. 1986). As the water flows past the outlet, the discharge is decreased because of the outflow, hence the velocity of flow and velocity head are also reduced. The total energy remains the same (ignoring the negligible friction loss that occurs over the length of the opening) hence the reduction in velocity head is balanced by an increase in pressure. A net increase of pressure, in the direction of flow, results if the pressure head recovery at the outlet is greater than the friction loss between the gates (Smith et al. 1986).

The flow velocities in the larger diameter layflat were generally lower, hence the pressure head recoveries were also lower and the pressure increase much less pronounced. This was also observed in the tests involving the use of the adjustable valves and hence lower flow rates.

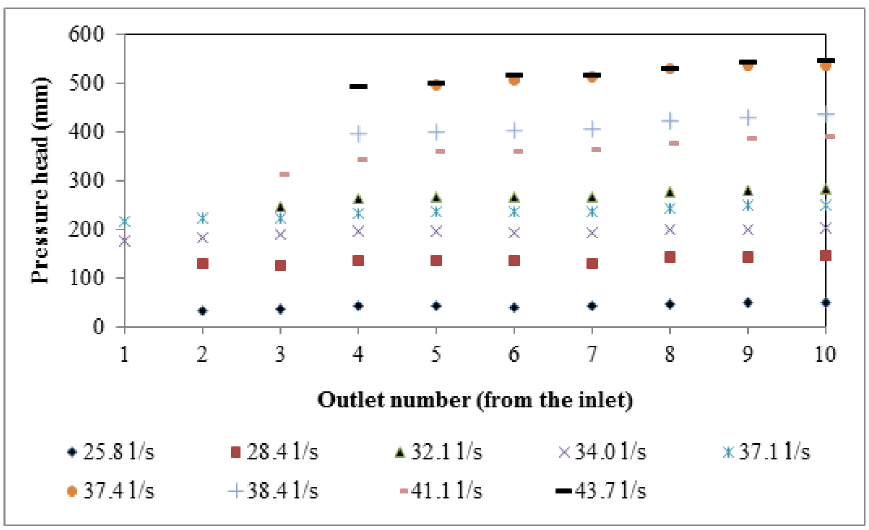


Figure A.4: Variation of pressure along the length of the 222.8 mm diameter layflat (without valves)

Outlet discharge

The outlet discharge profiles are presented in Figures A.5 and A.6 below. Random variations in the outflow are masking any trends (which would be expected to follow those evident in the pressure profiles). The trials performed on the 222.8 mm layflat with the adjustable valves at fully open position were however an exception, where outflows appeared to decrease slightly towards the downstream end. The reasons for the greater and non-systematic variation in outflows are manifold and include errors in the capture and measurement of the flows, random variations due to variations in the installation of the outlets (differences in the protrusion into the flow and the angle to the flow), manufacturing tolerances of the outlets, and for the trials with valves installed differences in the fit and closure of the valves. For both pipes the maximum flow rate delivered was 6 l/s and was only possible in the tests with the adjustable valves removed.

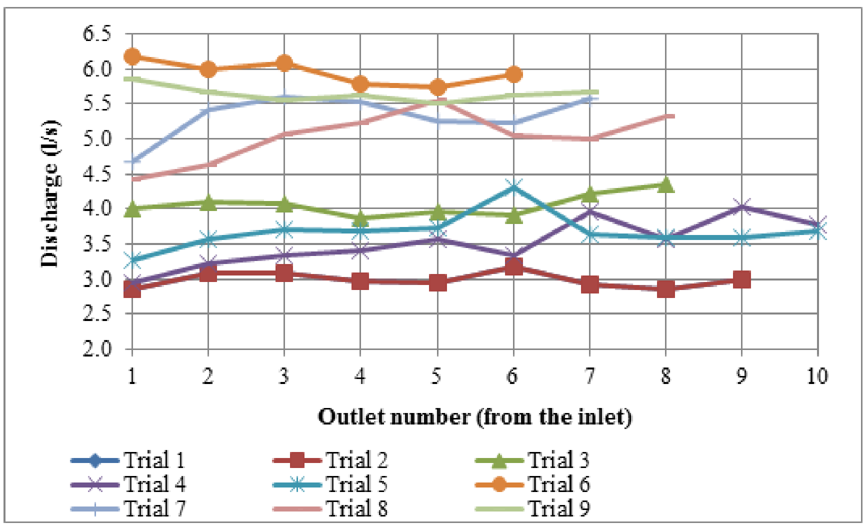


Figure A.5: Discharge variation along the length of the 222.8 mm layflat (without valves)

Smith et al. (2005) have shown that for efficient irrigation of the very long furrows used in the Australian cotton industry, furrow flow rates of about 6 l/s are required. For this gated fluming to be a practical option it must be able to deliver flow rates of this magnitude uniformly. It is obvious from these results that Flexiflume gates with the valves installed cannot deliver the flow rates required at the low pressure heads typically available from existing irrigation head ditches. Removal of the valves gives high flow rates but the high momentum of falling water may cause significant erosion in the furrow. The use of socks on the outlets (Figure A.7) might mitigate this erosion but the effect of the socks on the gate characteristic needs to be investigated. New outlet configurations will be required for higher flow rates or lower pressures.

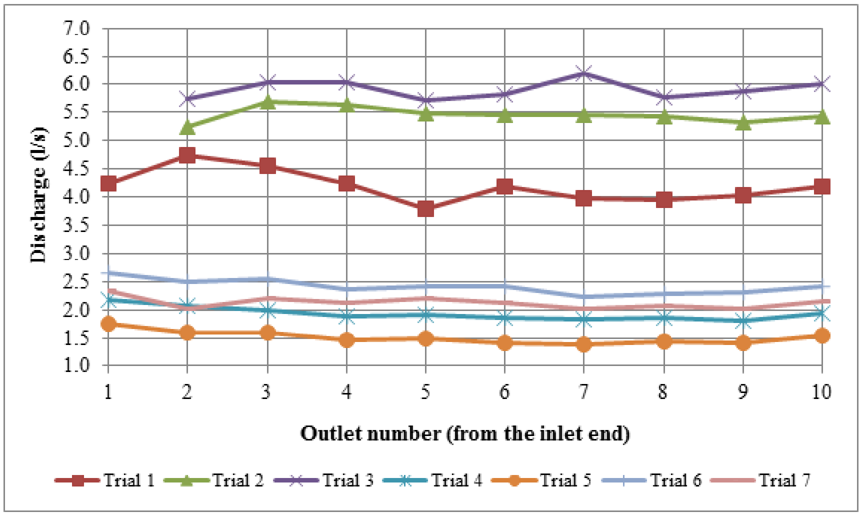


Figure A.6: Discharge variation along the length of the 425 mm layflat (Trials 1 - 3 without valves; Trials 4 - 7 with valves)

Pipe friction - outlets installed

With the outlets installed and spatially varied flow occurring in the pipeline, the slope of the energy line varies along the length of the pipeline. To determine the position of the energy line, the velocity head upstream of each outlet was added to the measured HGL (manometer reading). In this case the velocity head was taken as $1.1\,V^2/2g$ after Smith et al. (1986).

For each trial a calculated energy line was adjusted by varying the value of the Hazen-Williams coefficient to give the best fit to the measured energy line. Starting from the measured energy at the downstream end of the pipeline, the energy line was calculated progressively using a modified Hazen-Williams equation:

$$h_f = F_N \beta_f N L_s \left(\frac{V}{0.849 C_{HW} (\frac{D}{4})^{0.63}} \right)^{1.852} \tag{A.7}$$

where N is the number of outlets from the closed end and L_s is the outlet spacing. The factor F_N (Christiansen 1941) accounts for the effect on friction losses of the spatial variation of the flow. In this approach, uniform outflows are assumed and

Figure A.7: Socks on outlets

the head loss is obtained by multiplying the friction which would have occurred in a similar pipeline without outlets by the factor F_N, which is a function of the number of outlets and is given by:

$$F_N = \frac{1}{m+1} + \frac{1}{2N} + \frac{(m-1)^{0.5}}{6N^2} \tag{A.8}$$

where m is the exponent on the velocity term in the relevant flow equation, in this case $m = 1.852$.

For the 222.8 mm diameter pipe the best fit values for C_{HW} varied from 65 to 100 with a mean of 80 for the 10 trials. This mean value is significantly lower than the value for the same pipe with no outlets installed and reflects the additional friction loss caused by the protrusion of the gates into the flow in the pipeline.

Gate characteristic equation

The outflows from the 222.8 mm diameter pipe from all trials are shown in Figure A.8 plotted against the relevant measurements of pressure head and velocity head. These data show the expected strong relationship between outflow and pressure head but show no evidence of any influence on flow rate of velocity head. This contrasts with the results of Kincaid & Kemper (1982) and Smith et al. (1986) who showed that increasing velocity head serves to reduce the outflow rate. It is not clear from this study why the velocity head appears to have no impact on outlet discharge even when in some cases it comprises about 50% of the total head. The unique shape of the Flexiflume outlet may be one possibility, but further research is required for a definitive answer.

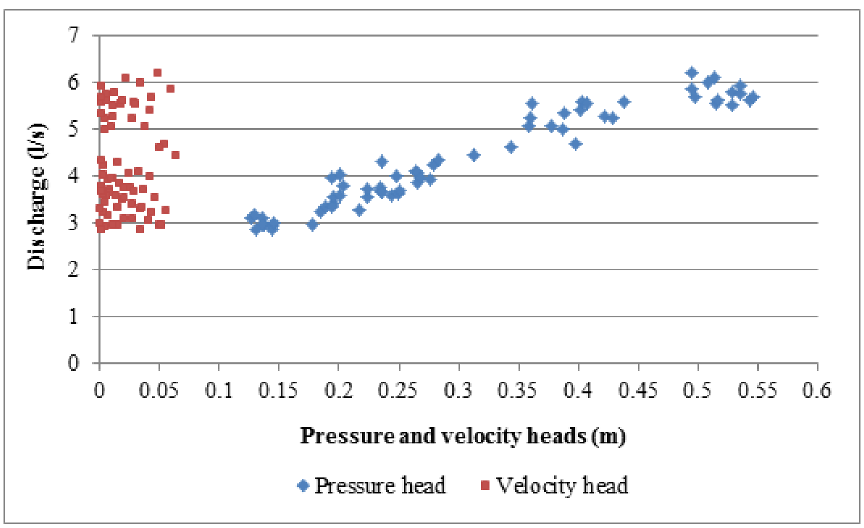


Figure A.8: Plot of discharge, pressure and velocity heads for the 222.8 mm diameter pipe

Various forms of equation were tried for the head-discharge characteristic for the outlets (including three parameter forms involving velocity head) but none fitted the data better than a two parameter power curve similar in form to the standard orifice equation. The two sets of data for the two pipe diameters were combined

(Figure A.9) to give a gate characteristic of the form:

$$Q = 7.9621 {H_p}^{0.4994} \tag{A.9}$$

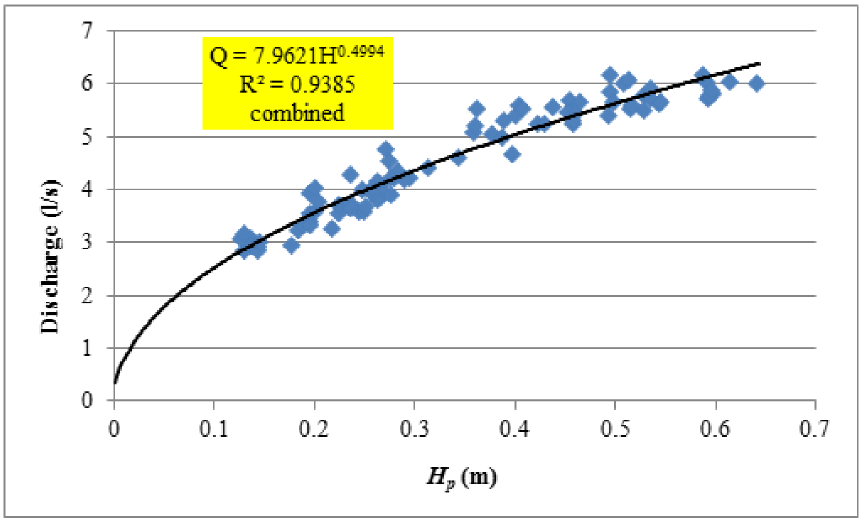


Figure A.9: Discharge-pressure for the combined data (valve seats)

The combined data for the case of adjustable valves set at fully-open position did not produce a good relationship (Figure A.10). In this case the scatter in the data was substantial and probably reflected the difficulty in adjusting the valve inserts with any degree of precision. It suggests that an acceptable uniformity of outflows would be difficult to achieve using the adjustable valves and that performance would be improved by removing the valves.

Within the limits of experimental accuracy, it is proposed that Eqn. A.9 above may be used in the hydraulic design of layflat fluming using the Flexiflume outlets, which is common in the irrigation industry in Australia, but with the adjustable inserts removed altogether.

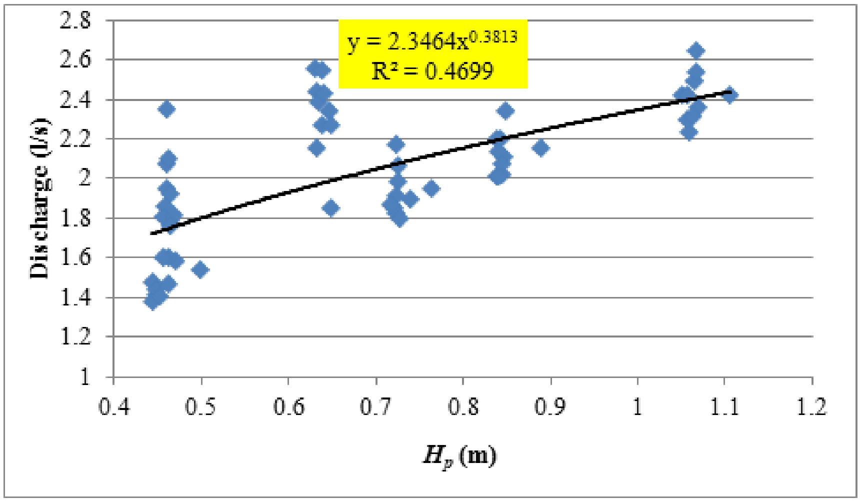


Figure A.10: Discharge-pressure for the combined data (with adjustable valves)

GPIPE SIMULATIONS

The gate characteristic equation for the combined data (with the use of valves seats only) was incorporated into the GPIPE program (Smith et al. 1986). This program was used to simulate outlet discharge and pressure profiles for the two pipe diameters with the Hazen-Williams coefficient set at the measured value of 80. The simulations were designed to converge on the total discharge and pressure head in the supply line.

The measured and simulated (using the GPIPE program) discharge and pressure profiles are shown in Figures A.11 to A.14. These figures show that the GPIPE program, given an accurate gate characteristic, can be used to predict with a more than reasonable accuracy the pressures in and outflows from gated flexible fluming. There is a good correlation between the measured and predicted pressure profiles. In the case of the discharge profiles the greater scatter in the measured discharges caused a lesser correlation.

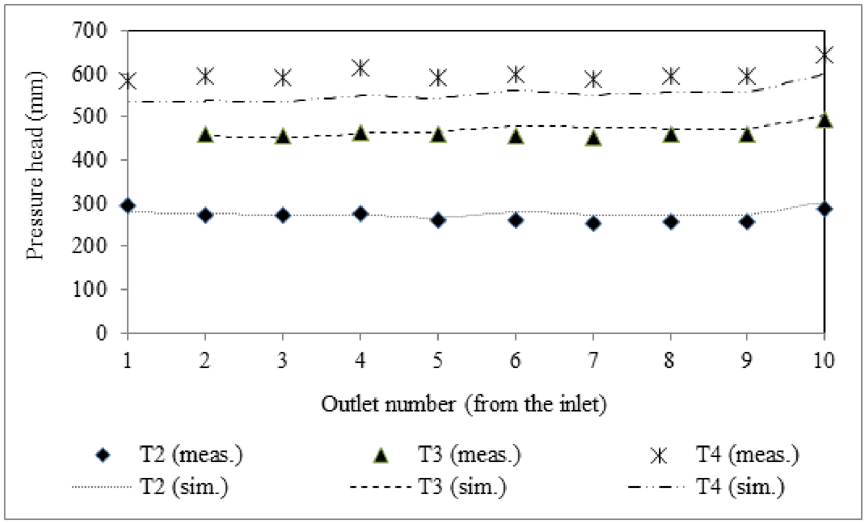


Figure A.11: Measured versus simulated pressure for the 425 mm diameter pipe

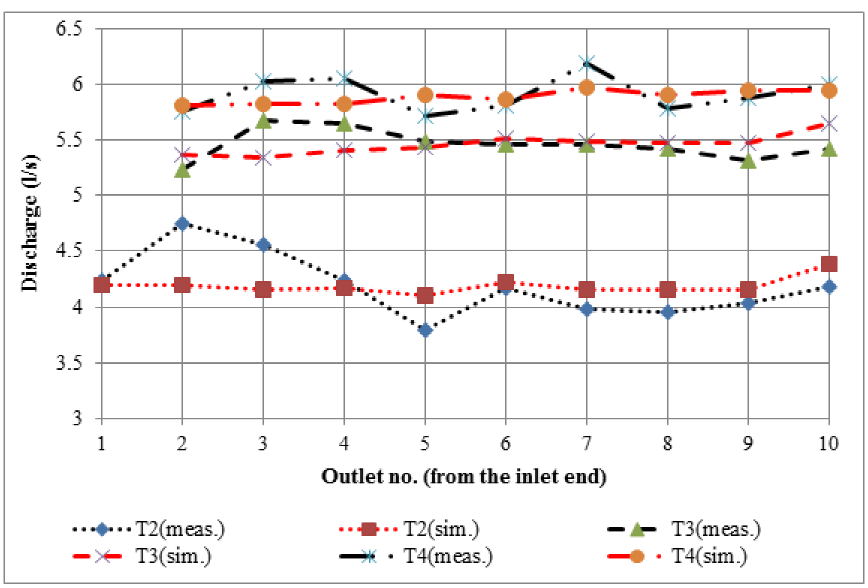


Figure A.12: Measured versus simulated discharge for the 425 mm diameter pipe

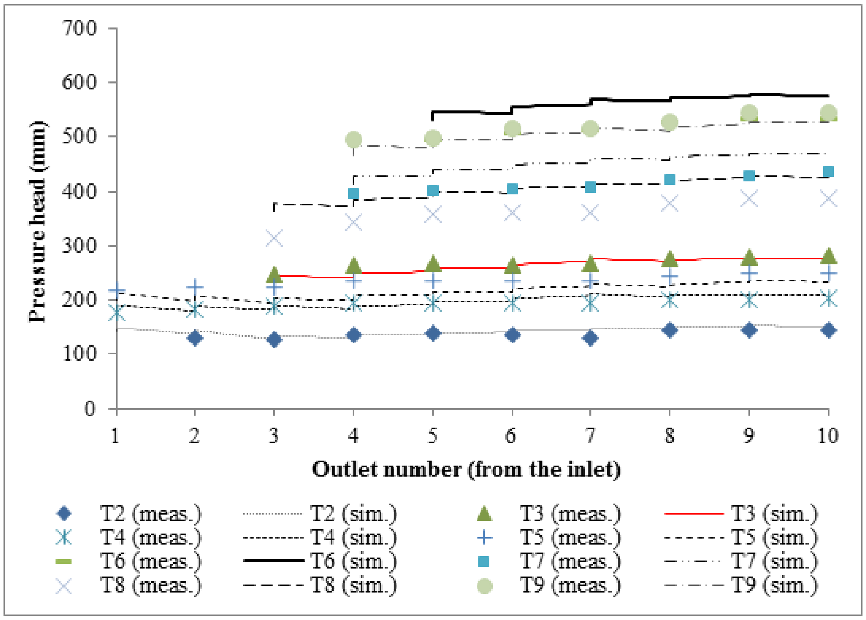


Figure A.13: Measured versus simulated pressure for the 222.8 mm diameter pipe

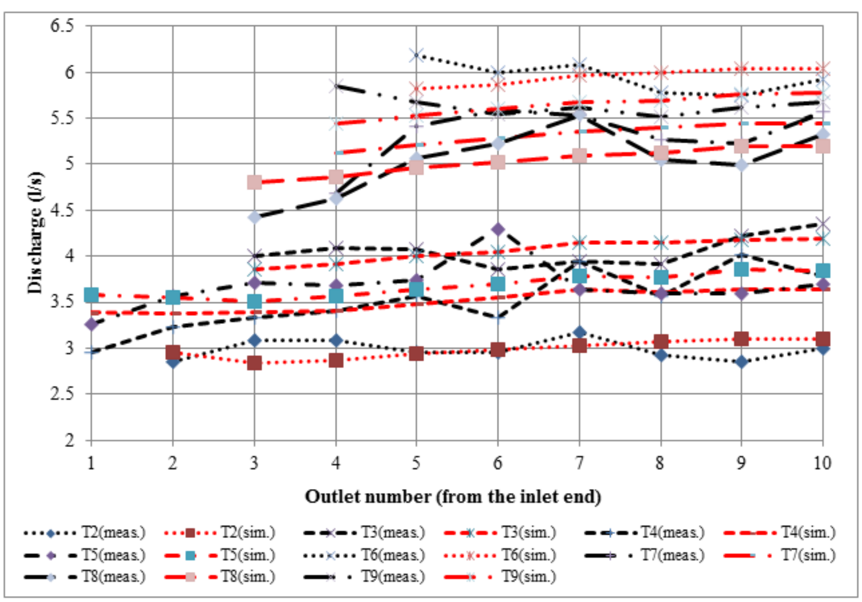


Figure A.14: Measured versus simulated discharge for the 222.8 mm diameter pipe

CONCLUSIONS

Laboratory experiments were conducted to investigate the hydraulic characteristics of 'Flexiflume', a type of layflat which is widely used in the irrigation industry in Australia. The geometrical relationships derived were found to be similar to those obtained by Humpherys and Lauritzen (1964), confirming the validity of applying friction loss relationships to Flexiflume.

The pressure heads in the two pipes, measured immediately upstream of the outlets, generally increased slightly towards the downstream end. This can be attributed to the pressure head recovery at each outlet being greater than the friction loss between the gates.

Any similar slight trend in the pattern of outflows was masked by the scatter in the measurements of outflow. For the Flexiflume outlets with the adjustable valves removed, outlet discharges up to 6 l/s were measured for both pipes, while with the inserts installed and in the fully open position the maximum outflow was 2.5 l/s. All trials were conducted at pressure heads less than 1100 mm. This implies that the outlets with the adjustable valves in fully open position do not have the capacity to supply the higher flow rates required at the lower heads typically available in the furrow irrigation systems employed in the Australian cotton industry. Only by removal of the valves can the desired flow rates be delivered. A head-discharge equation was developed for the gates (with and without the adjustable valves), having a form of a power equation similar to the standard orifice equation. In the regression analyses to determine the gate characteristic equation, velocity head was found not to have any significant impact in predicting the outlet discharge. The unique shape of the outlet is a possible cause of this but further research and analysis is required.

The Hazen-Williams friction coefficient (C_{HW}) for the fluming with outlets installed was determined to be a low 80 (compared with the recommended value of 145 for the fluming without inserts). This additional friction loss with the outlets installed is attributed to the protrusion of the gates into the flow continuing along the pipeline.

Simulations using the program GPIPE produced a good correlation between the measured and simulated discharge and pressure profiles, implying that the program may be a useful tool in the hydraulic design of layflat gated pipes.

Appendix B

St George Field Trials (2010/11 Irrigation Season)

The complete data for the trials undertaken during the 2010/11 irrigation season are shown in this appendix. The data has been used in Chapters 5 and 6 and referred to in Chapter 7. The infiltration parameters a, k, f_o and p, r, A_o were determined using the SISCO and IPARM models respectively.

Note: Model and wheel-tracked furrows are shaded in black and gray respectively.

B.0.1 Trial 1A

Date: 25/01/2011

Field length: 970 m

Slope: 0.0007 m/m

Inflow: 6.0 l/s

Furrow spacing: 1 m

Deficit: 80 mm

Table B.1: Furrow dimensions - Trial 1A

Top width	800 mm
Middle width	520 mm
Bottom width	250 mm
Total depth	150 mm

Table B.2: Advance data - Trial 1A

	Furrow number							
	1	2	3	4	5	6	7	8
Distance (m)	Advance time (mins)							
0	1	1	1	1	1	0	0	1
250	69	58	109	84	90	49	54	42
500	160	142	205	195	178	128	125	95
650	202	194	265	237	221	177	179	132
800	288	242	300	287	283	218	238	166
920	293	291	343	331	332	259	283	191

Table B.3: Infiltration parameters - Trial 1A

	F1	F2	F3	F4	F5	F6	F7	F8
a	0.044541511	0.250205198	0	0	0	0.274178969	0.278927044	0.216119657
k	0.047177402	0.020363109	0.089595024	0.081133306	0.08150293	0.015584332	0.013858161	0.011221403
f_o	0.000121138	0	0	0	4.15608E-05	0	0.000101876	0
p	6.28598	8.28255	0.96194	2.37426	3.2849	9.36374	12.12373	9.52913
r	0.86797	0.83043	1.17507	1.02634	0.97273	0.82419	0.76677	0.8681
A_o	0.05238	0.05238	0.05238	0.05238	0.05238	0.05238	0.05238	0.05238

B.0.2 Trial 2A

Date: 2/02/2011

Field length: 970 m

Slope: 0.0007 m/m

Inflow: 5.0 l/s

Furrow spacing: 1 m

Deficit: 80 mm

Table B.4: Furrow dimensions - Trial 2A

Top width	800 mm
Middle width	520 mm
Bottom width	250 mm
Total depth	150 mm

Table B.5: Advance data - Trial 2A

	Furrow number							
	1	2	3	4	5	6	7	8
Distance (m)	Advance time (mins)							
0		1	1	0	0	0	0	0
500	174	175	243	256	242	181	115	106
650	228	229	312	316	321	233	229	223
800		283	378	379		296		
920	325	327	419		442	327	344	239

Table B.6: Infiltration parameters - Trial 2A

	F1	F2	F3	F4	F5	F6	F7	F8
a	0.00057247	0	0.10982866	0	0.117675858	0	0.583168365	0.591569033
k	0.06166912	0.06217972	0.057478448	0.101933889	0.057629065	0.064599246	0.003807076	0.003090066
f_o	0	1.79367E-06	0	0	0	0	0	0
p	3.2324	3.24086	1.031	0.68117	1.73603	2.61636	29.14773	24.78392
r	0.97703	0.97565	1.12352	1.19087	1.02921	1.01005	0.586	0.63676
A_o	0.04583	0.04583	0.04583	0.04583	0.04583	0.04583	0.04583	0.04583

B.0.3 Trial 3A

Date: 16/02/2011

Field length: 970 m

Slope: 0.0007 m/m

Inflow: 3.82 l/s

Furrow spacing: 1 m

Deficit: 82 mm

Table B.7: Furrow dimensions - Trial 3A

Top width	800 mm
Middle width	600 mm
Bottom width	340 mm
Total depth	125 mm

Table B.8: Advance data - Trial 3A

	Furrow number							
	1	2	3	4	5	6	7	8
Distance (m)	Advance time (mins)							
0	1	1	2	1	1	0	0	0
250	104	152	168	169	116	75	74	58
500	252	265		313	292	213	186	135
650	332	354	422	353	358	288	291	179
800	389	413		413	436	346		217
920	480	493	510	510	503	389	403	276

Table B.9: Infiltration parameters - Trial 3A

	F1	F2	F3	F4	F5	F6	F7	F8
a	0.128340428	0.0678046481	0	0.079919044	0.076922419	0.151071838	0.306957769	0
k	0.042018926	0.0609109038	0.098421768	0.060527818	0.060562965	0.029981406	0.014049923	0.01764837
f_o	0	0	0	0	0	0	0	0.000131196
p	3.61869	1.30598	0.38022	0.68225	2.10349	4.66324	8.03399	0
r	0.8984	1.06037	1.24384	1.16169	0.97592	0.88045	0.78587	0.01764837
A_o	0.03901	0.03901	0.03901	0.03901	0.03901	0.03901	0.03901	0.03901

B.0.4 Trial 4A

Date: 2/03/2011

Field length: 970 m

Slope: 0.0007 m/m

Inflow: 3.3 l/s

Furrow spacing: 1 m

Deficit: 90 mm

Table B.10: Furrow dimensions - Trial 4A

Top width	800 mm
Middle width	500 mm
Bottom width	300 mm
Total depth	125 mm

Table B.11: Advance data - Trial 4A

	Furrow number							
	1	2	3	4	5	6	7	8
Distance (m)	Advance time (mins)							
0	0	0	0	0	0	0	0	0
250				191	116			
500		342			241			
650	385	388	390	366	369	285	283	
800	459	492	511	492	478	371	309	301
920	561		576	570	534			351

Table B.12: Infiltration parameters - Trial 4A

	F1	F2	F3	F4	F5	F6	F7	F8
a	0	0	0.141462587	0	0.25059236	0.013323721	0	0.02913178
k	0.07159797	0.090140089	0.043368645	0.087787069	0.022250116	0.037999323	0.047296073	0.032515561
f_o	6.10197E-05	0	0	0	0	0.000117845	0	3.81532E-05
p	3.31024	0.5575	3.22908	1.18025	5.55729	7.58655	0.00105	4.45591
r	0.89057	1.17466	0.88738	1.0526	0.80987	0.78737	2.36237	0.90946
A_o	0.03459	0.03459	0.03459	0.03459	0.03459	0.03459	0.03459	0.03459

B.0.5 Trial 1B

Date: 26/01/2011

Field length: 714 m

Slope: 0.0007 m/m

Inflow: 1.5 l/s

Furrow spacing: 1 m

Deficit: 80 mm

Table B.13: Furrow dimensions - Trial 1B

Top width	800 mm
Middle width	520 mm
Bottom width	250 mm
Total depth	150 mm

Table B.14: Advance data - Trial 1B

	Furrow number							
	1	2	3	4	5	6	7	8
Distance (m)	Advance time (mins)							
0	1	1	0	1	1	1	1	4
200	130	95	117	81	186	138	113	29
300	383	274	35	308	462	375	359	350
400	625	468	552	609	710	600	577	488
500	675	601	613	704	729	709	700	584
620	449	585	493	742	397	379	630	380

Table B.15: Infiltration parameters - Trial 1B

	F1	F2	F3	F4	F5	F6	F7	F8
a	0.478042795	0.543430244	0.547033152	0.51050781	0.364352778	0.453062961	0.512887298	0
k	0.006920838	0.004048584	0.004131562	0.00493681	0.015115517	0.008058644	0.005470601	0.088439743
f_o	0	0	0	0	0	0	0	0
p	11.05493	16.53136	15.83002	13.59202	5.50305	9.61193	13.67949	0.78993
r	0.57043	0.52603	0.52655	0.55481	0.66719	0.59256	0.5397	1.01063
A_o	0.01926	0.01926	0.01926	0.01926	0.01926	0.01926	0.01926	0.01926

B.0.6 Trial 2B

Date: 3/02/2011

Field length: 714 m

Slope: 0.0007 m/m

Inflow: 1.6 l/s

Furrow spacing: 1 m

Deficit: 80 mm

Table B.16: Furrow dimensions - Trial 2B

Top width	800 mm
Middle width	520 mm
Bottom width	250 mm
Total depth	150 mm

Table B.17: Advance data - Trial 2B

	Furrow number							
	1	2	3	4	5	6	7	8
Distance (m)	Advance time (mins)							
0	0	1	0	9	9	1	0	0
200	221	83	205	120	235	188	135	172
400	289	188	430	394	478	398	360	24
500	524	259	542	538	603	514	466	357
600		385	648	672	704	626	563	426
650	645	476	730	755	917		623	440

Table B.18: Infiltration parameters - Trial 2B

	F1	F2	F3	F4	F5	F6	F7	F8
a	0	0	0	0.356240226	0	0.044680616	0.225497936	0
k	0.057561939	0.016113167	0.079255799	0.011571209	0.075737493	0.058098635	0.021208158	0.048500797
f_o	6.89246E-05	0.000136582	2.27488E-05	0	7.60185E-05	2.48557E-05	0	0
p	2.72704	16.73022	1.41644	7.22595	2.70166	1.72914	3.48238	0.35802
r	0.84288	0.59938	0.93156	0.67723	0.81161	0.90835	0.81133	1.23022
A_o	0.02016	0.02016	0.02016	0.02016	0.02016	0.02016	0.02016	0.02016

B.0.7 Trial 3B

Date: 17/02/2011

Field length: 714 m

Slope: 0.0007 m/m

Inflow: 1.54 l/s

Furrow spacing: 1 m

Deficit: 80 mm

Table B.19: Furrow dimensions - Trial 3B

Top width	900 mm
Middle width	640 mm
Bottom width	350 mm
Total depth	200 mm

Table B.20: Advance data - Trial 3B

	Furrow number							
	1	2	3	4	5	6	7	8
Distance (m)	Advance time (mins)							
0	0	0	0	0	0	0	0	0
200	71	165	97	194	157	219	205	164
400	146	391	323	416	415		308	384
500	189	547		538		581	532	489
620		627	515	670	658	660		
670	312	37	562		729	767		650

Table B.21: Infiltration parameters - Trial 3B

	F1	F2	F3	F4	F5	F6	F7	F8
a	0	0.177880584	0.301283981	0.095746112	0.197924326	0	0	0.096581769
k	0.00984174	0.029488104	0.011597809	0.04811098	0.026673695	0.082551726	0.047176992	0.042478271
f_o	0.00010815	0	0	0	0	6.97778E-06	0.000113666	0
p	9.62082	2.52233	5.51383	1.60252	2.78105	1.01665	4.07807	1.7701
r	0.74283	0.84845	0.75534	0.91489	0.83162	0.97986	0.77151	0.91442
A_o	0.02034	0.02034	0.02034	0.02034	0.02034	0.02034	0.02034	0.02034

B.0.8 Trial 3B

Date: 1/03/2011

Field length: 714 m

Slope: 0.0007 m/m

Inflow: 3.2 l/s

Furrow spacing: 1 m

Deficit: 90 mm

Table B.22: Furrow dimensions - Trial 4B

Top width	900 mm
Middle width	640 mm
Bottom width	350 mm
Total depth	200 mm

Table B.23: Advance data - Trial 4B

	Furrow number							
	1	2	3	4	5	6	7	8
Distance (m)	Advance time (mins)							
0	0	0	0	0	0	0	0	0
200	79	117	69	113	100	140	154	154
400	152	246	210	259	276	306	281	
500			300	309		421	435	435
620		329			445			
670		406	412		494			

Table B.24: Infiltration parameters - Trial 4B

	F1	F2	F3	F4	F5	F6	F7	F8
a	0	0	0.37045	0.08276	0.2405	0	0	0.06322
k	0.043362973	0.07824	0.01312	0.06117	0.03095	0.0903	0.08619	0.08816
f_o	0	1.266E-05	0	0	0	0.0002	0.00022	6.978E-05
p	1.95499	1.8545	9.20098	2.52418	4.65069	3.62904	4.04333	2.3482
r	1.05916	0.98717	0.70801	0.91855	0.80075	0.81701	0.79782	0.88241
A_o	0.03349	0.03349	0.03349	0.03349	0.03349	0.03349	0.03349	0.03349

B.0.9 Cumulative infiltration curves (based scaled infiltration)

Note: Kostiakov-Lewis equation (Eqn. 2.4) used to compute cumulative infiltration.

Table B.25: Scaled infiltration parameters and scaled cumulative infiltration for Trials 1A, 2A, 3A, 4A and 2B

	Trial Number				
	1A	2A	3A	4A	2B
a	0.22640	1.00E-07	0.01095	0.11883	0.51051
k	0.03256	0.10496	0.08464	0.06090	0.00495
f_o	0	5.35E-05	1.86E-05	0	0
Time (min)	Cumulative infiltration (m^3/m)				
0	0	0	0	0	0
50	0.07895	0.10764	0.08927	0.09694	0.03646
100	0.09236	0.11031	0.09088	0.10526	0.05194
150	0.10124	0.11299	0.09221	0.11045	0.06389
200	0.10806	0.11566	0.09342	0.11429	0.07400
250	0.11366	0.11834	0.09457	0.11737	0.08292
300	0.11845	0.12101	0.09569	0.11994	0.09101
350	0.12265	0.12369	0.09677	0.12215	0.09847
400	0.12642	0.12636	0.09784	0.12411	0.10541
450	0.12984	0.12904	0.09888	0.12586	0.11194
500	0.13297	0.13171	0.09992	0.12744	0.11813
550	0.13587	0.13439	0.10095	0.12889	0.12402
600	0.13857	0.13706	0.10197	0.13023	0.12965
650	0.14111	0.13974	0.10298	0.13148	0.13506
700	0.14349	0.14241	0.10398	0.13264	0.14027
750	0.14575	0.14509	0.10499	0.13373	0.14530
800	0.14790	0.14776	0.10598	0.13476	0.15016
850	0.14994	0.15044	0.10698	0.13574	0.15488
900	0.15190	0.15311	0.10796	0.13666	0.15947
950	0.15377	0.15579	0.10895	0.13754	0.16393
1000	0.15556	0.15846	0.10993	0.13838	0.16828

Table B.26: Actual infiltration parameters and actual cumulative infiltration for Trials 1A, 2A, 3A and 4A

	Trial Number			
	1A	2A	3A	4A
a	0	0.11768	0.06806	0
k	0.08150	0.05763	0.06083	0.09014
f_o	4.156E-05	0	0	0
Time (min)	Cumulative infiltration (m^3/m)			
0	0	0	0	0
50	0.08358	0.09132	0.07939	0.09014
100	0.08566	0.09908	0.08323	0.09014
150	0.08774	0.10392	0.08556	0.09014
200	0.08982	0.10750	0.08725	0.09014
250	0.09189	0.11036	0.08858	0.09014
300	0.09397	0.11276	0.08969	0.09014
350	0.09605	0.11482	0.09063	0.09014
400	0.09813	0.11664	0.09146	0.09014
450	0.10021	0.11827	0.09220	0.09014
500	0.10228	0.11974	0.09286	0.09014
550	0.10436	0.12109	0.09347	0.09014
600	0.10644	0.12234	0.09402	0.09014
650	0.10852	0.12350	0.09453	0.09014
700	0.11060	0.12458	0.09501	0.09014
750	0.11267	0.12559	0.09546	0.09014
800	0.11475	0.12655	0.09588	0.09014
850	0.11683	0.12746	0.09628	0.09014
900	0.11891	0.12832	0.09665	0.09014
950	0.12099	0.12914	0.09701	0.09014
1000	0.12306	0.12992	0.09735	0.09014

Table B.27: Actual infiltration parameters and actual cumulative infiltration for Trials 1B, 2B, 3B and 4B

	Trial Number			
	1B	2B	3B	4B
a	0.51051	0.35624	0.17788	0
k	4.94E-03	0.01157	0.02949	0.07824
f_o	0	0	0	1.27E-05
Time (min)	Cumulative infiltration (m^3/m)			
0	0	0	0	0
50	0.04	0.04663	0.05914	0.07888
100	0.05182	0.05968	0.06690	0.07951
150	0.06373	0.06896	0.07190	0.08014
200	0.07381	0.07640	0.07568	0.08078
250	0.08272	0.08272	0.07874	0.08141
300	0.09079	0.08827	0.08134	0.08204
350	0.09822	0.09326	0.08360	0.08268
400	0.10515	0.09780	0.08561	0.08331
450	0.11167	0.10199	0.08742	0.08394
500	0.11784	0.10589	0.08907	0.08458
550	0.12372	0.10955	0.09059	0.08521
600	0.12933	0.11300	0.09201	0.08584
650	0.13473	0.11627	0.09333	0.08648
700	0.13992	0.11938	0.09457	0.08711
750	0.14494	0.12235	0.09573	0.08774
800	0.14979	0.12519	0.09684	0.08838
850	0.15450	0.12793	0.09789	0.08901
900	0.15908	0.13056	0.09889	0.08964
950	0.16353	0.13310	0.09984	0.09027
1000	0.16787	0.13555	0.10076	0.09091

Appendix C

Evaluation of alternative strategies

This appendix contains data from evaluations undertaken in Chapter 6 based on data presented in Chapter 5 and Appendix B.

C.1 Varying the flow rate

The effect of varying Q on AE, RE and TCO is shown in the tables and figures below:

Table C.1: Trial 1A

Change in Q (%)	Q (l/s)	Automated system TCO=280 min		Actual performance TCO=424 min	
		AE (%)	RE (%)	AE (%)	RE (%)
100	12	39	100	25	100
75	10.5	44	100	29	100
50	9	51	100	34	100
30	7.8	59	100	39	100
20	7.2	64	100	42	100
10	6.6	70	100	46	100
0	6	72	93	51	100
-10	5.4	72	85	57	100
-20	4.8	73	76	64	100
-30	4.2	73	67	72	100
-50	3	74	48	97	96
-75	1.5	76	25	98	48

Table C.2: Trial 2A

Change in Q (%)	Q (l/s)	Automated system TCO=392 min		Actual performance TCO=392 min	
		AE (%)	RE (%)	AE (%)	RE (%)
100	10	33	100	33	100
75	8.75	38	100	38	100
50	7.5	44	100	44	100
30	6.5	50	100	51	100
20	6	54	100	55	100
10	5.5	60	100	60	100
0	5	66	100	65	100
-10	4.5	66	90	71	98
-20	4	66	80	71	87
-30	3.5	66	70	71	76
-50	2.5	67	51	72	55
-75	1.25	68	26	73	28

Table C.3: Trial 3A

Change in Q (%)	Q (l/s)	Automated system TCO=408 min		Actual performance TCO=456 min	
		AE (%)	RE (%)	AE (%)	RE (%)
100	7.64	43	100	38	100
75	6.69	49	100	44	100
50	5.73	57	100	51	100
30	4.97	65	100	59	100
20	4.58	70	100	64	100
10	4.20	76	100	69	100
0	3.82	84	100	76	100
-10	3.44	85	91	84	100
-20	3.06	85	80	90	95
-30	2.67	85	70	90	84
-50	1.91	85	50	91	60
-75	0.96	86	26	92	30

Table C.4: Trial 4A

Change in Q (%)	Q (l/s)	Automated system TCO=568 min		Actual performance TCO=584 min	
		AE (%)	RE (%)	AE (%)	RE (%)
100	6.60	39	100	38	100
75	5.78	44	100	43	100
50	4.95	52	100	50	100
30	4.29	59	100	58	100
20	3.96	64	100	63	100
10	3.63	70	100	69	100
0	3.30	73	95	76	100
-10	2.97	73	85	84	100
-20	2.64	73	76	94	100
-30	2.31	73	67	100	92
-50	1.65	74	48	99	66
-75	0.83	75	24	100	34

Table C.5: Trial 2B

Change in Q (%)	Q (l/s)	Automated system TCO=824 min		Actual performance TCO=936 min	
		AE (%)	RE (%)	AE (%)	RE (%)
100	3.2	36	100	32	100
75	2.8	41	100	36	100
50	2.4	48	100	42	100
30	2.08	56	100	49	100
20	1.92	60	99	53	100
10	1.76	62	94	58	100
0	1.6	62	86	64	100
-10	1.44	62	77	70	99
-20	1.28	62	69	70	89
-30	1.12	62	60	71	78
-50	0.8	62	43	71	56
-75	0.4	63	22	71	28

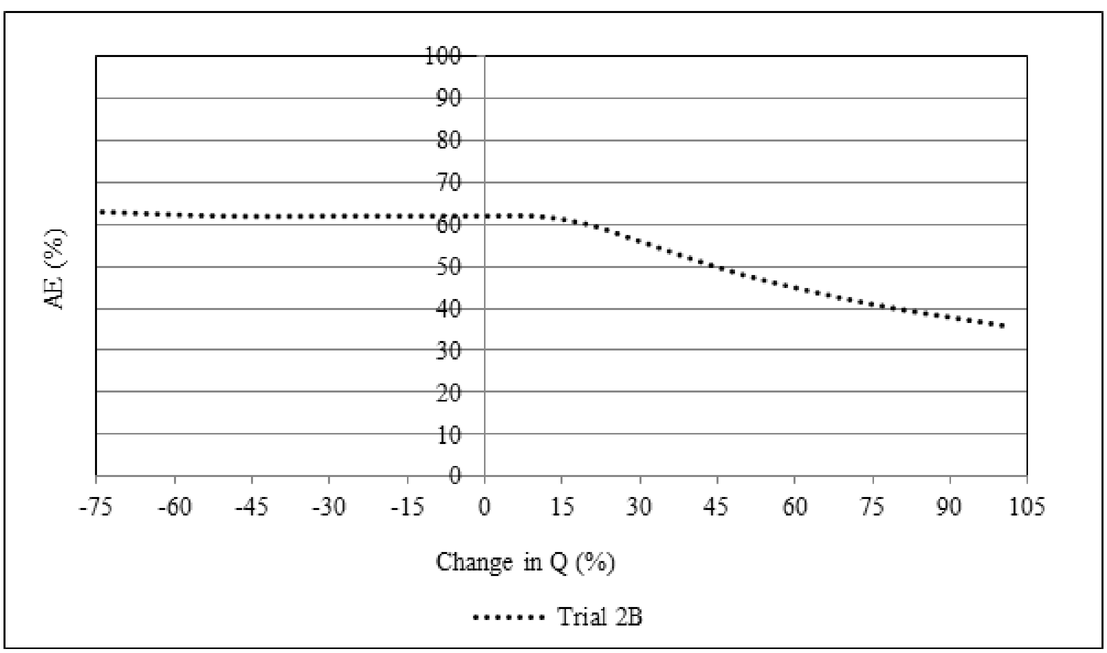


Figure C.1: Effect of varying Q on AE (Site B - scaled infiltration

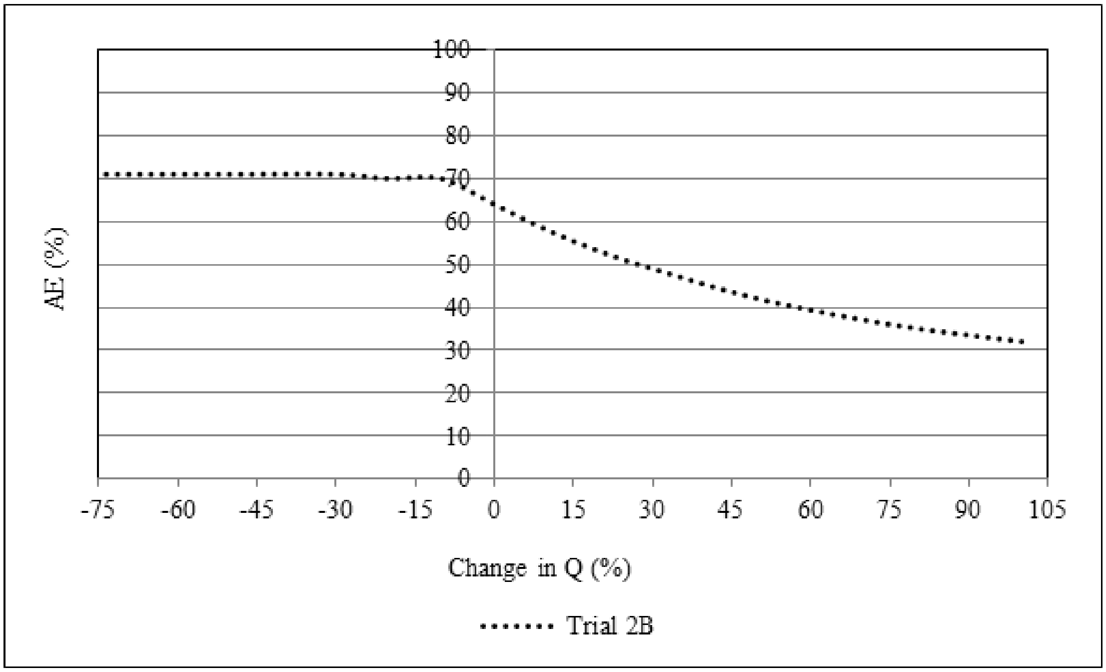


Figure C.2: Effect of varying Q on AE (Site B - actual infiltration)

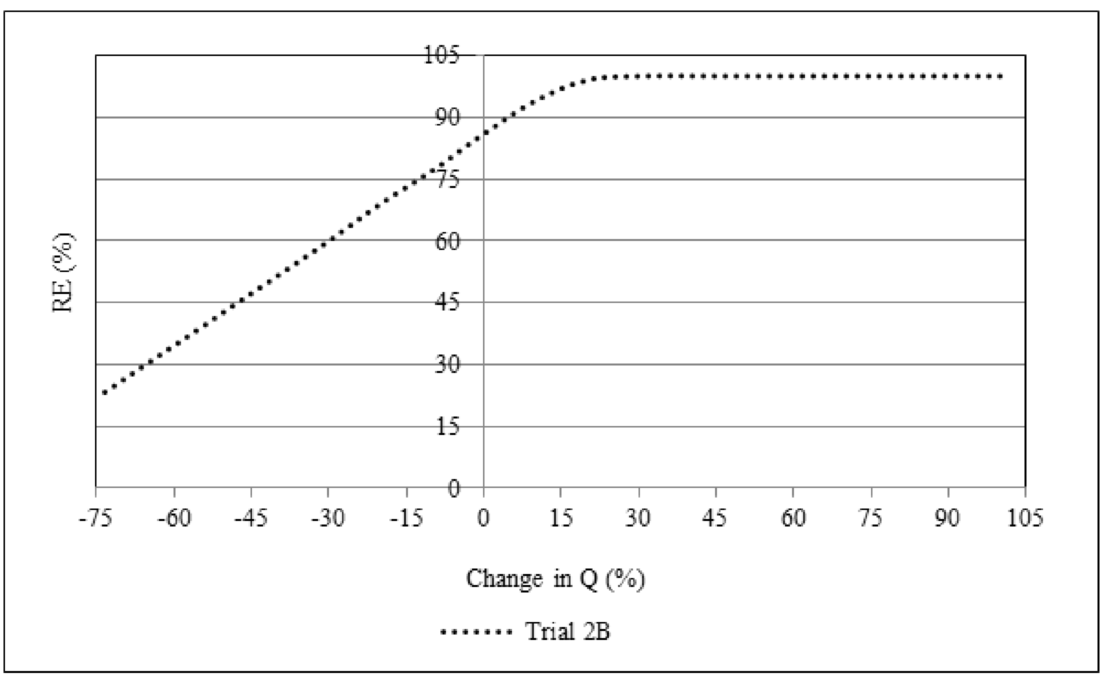


Figure C.3: Effect of varying Q on RE (Site B- scaled infiltration)

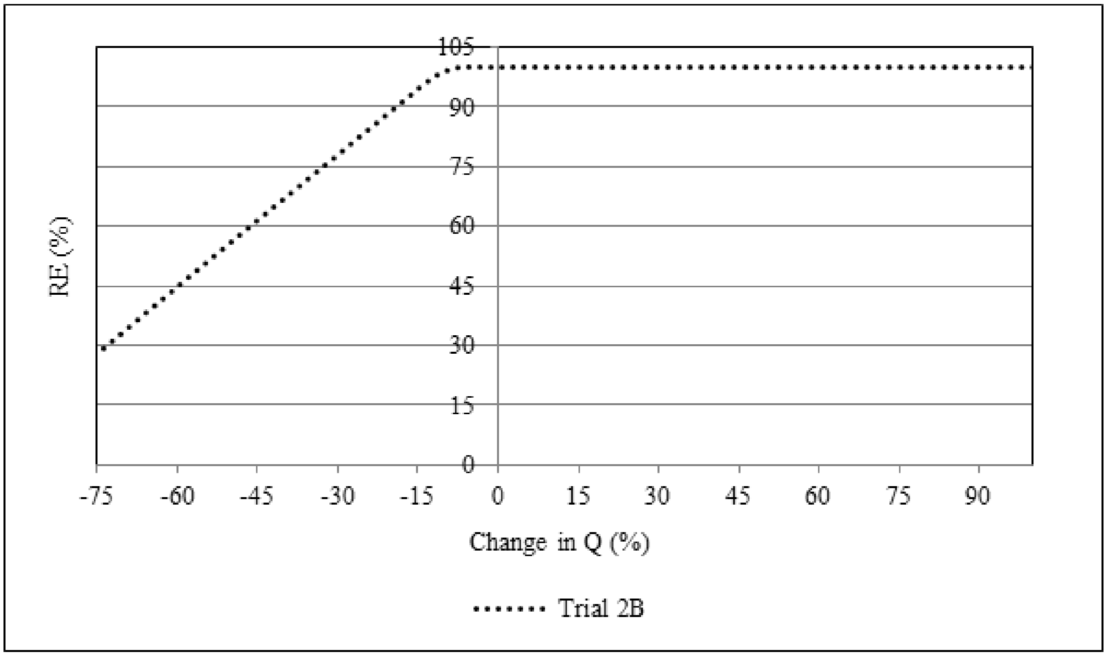


Figure C.4: Effect of varying Q on RE (Site B - actual infiltration)

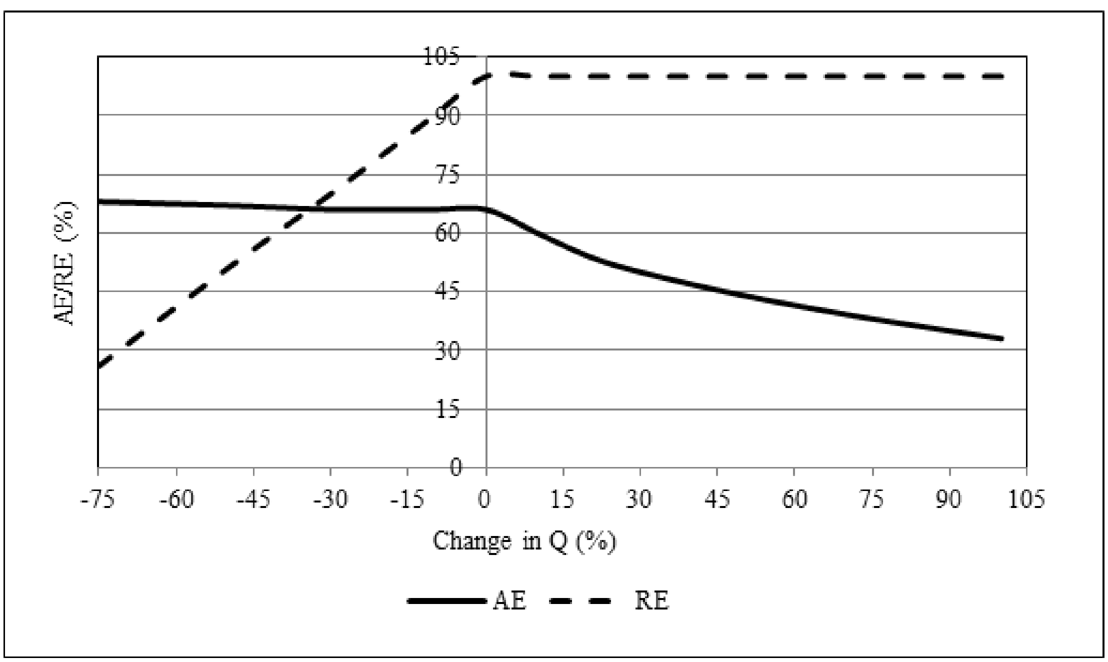


Figure C.5: Optimum Q for maximum AE and RE (Optimisation system - Trial 2A)

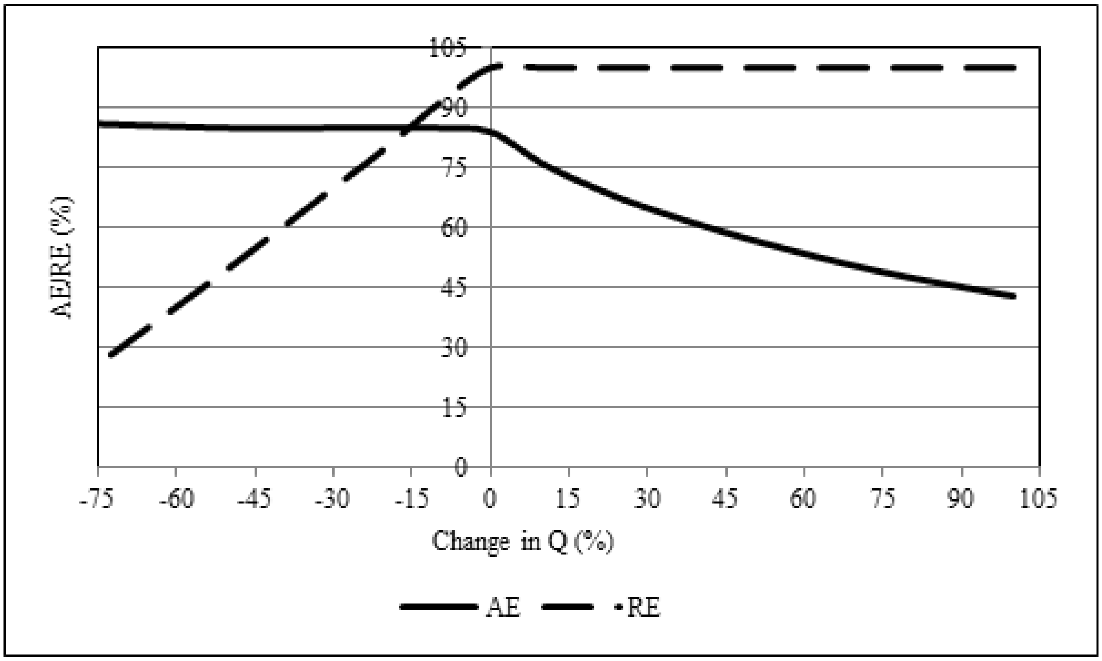


Figure C.6: Optimum Q for maximum AE and RE (Optimisation system - Trial 3A)

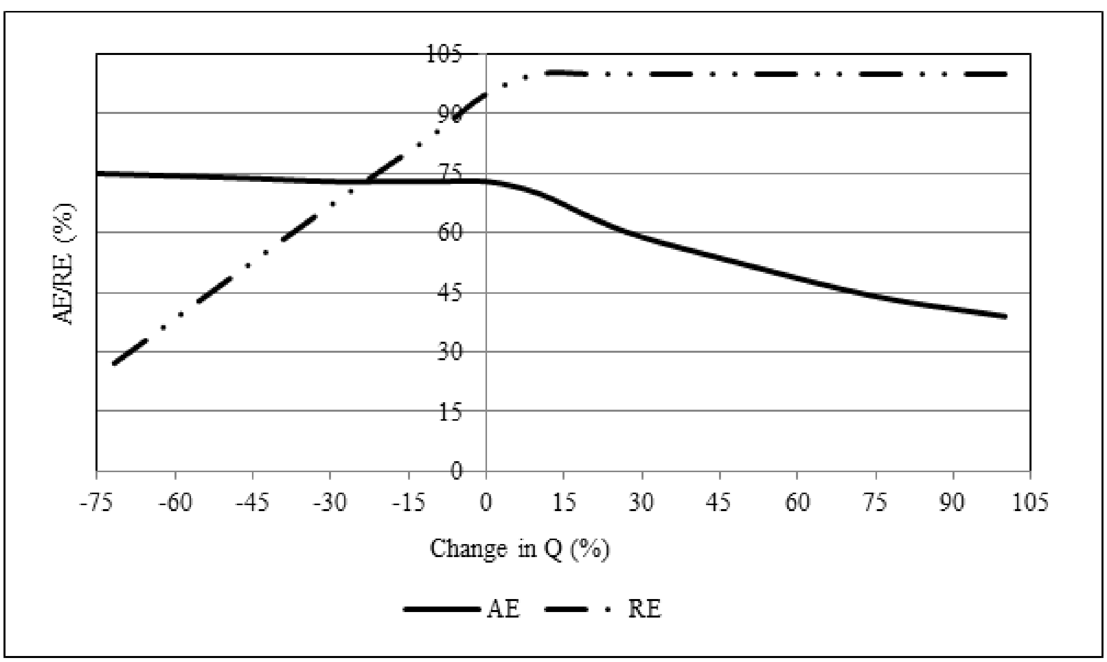


Figure C.7: Optimum Q for maximum AE and RE (Optimisation system - Trial 4A)

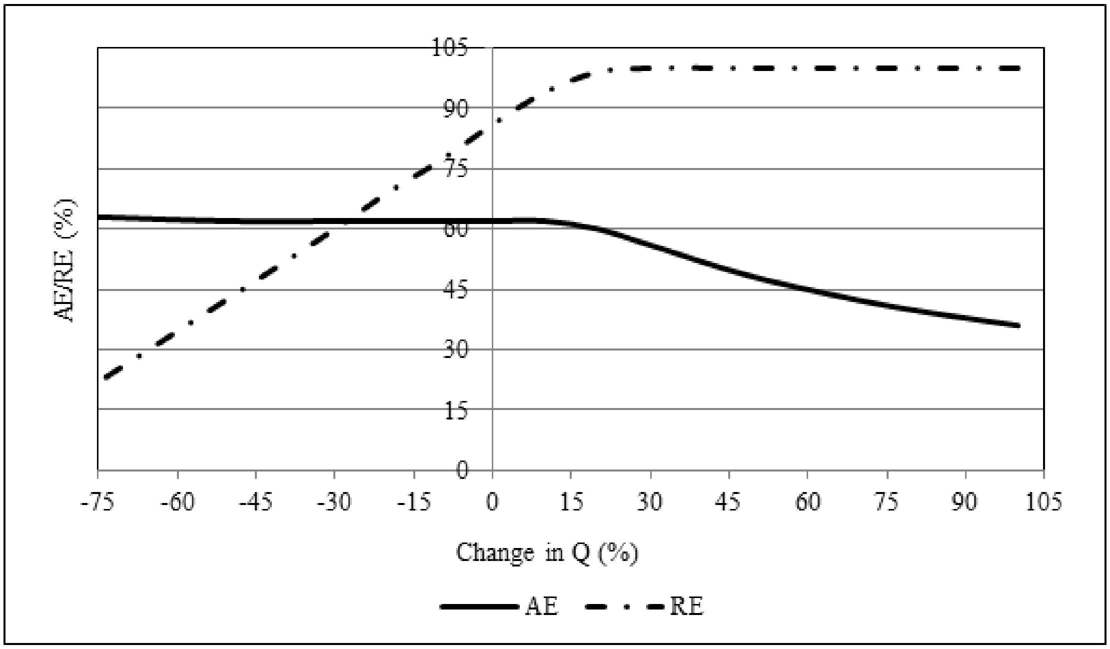


Figure C.8: Optimum Q for maximum AE and RE (Optimisation system - Trial 2B)

Table C.6: Effect of varied Q on AE and TCO (Optimisation system)

Site A												Site B		
Trial 1A			Trial 2A			Trial 3A			Trial 4A			Trial 2B		
Q (l/s)	AE (%)	TCO (min)	Q (l/s)	AE (%)	TCO (min)	Q (l/s)	AE (%)	TCO (min)	Q (l/s)	AE (%)	TCO (min)	Q (l/s)	AE (%)	TCO (min)
12	77	136	10	66	190	7.64	87	190	6.6	77	264	3.2	91	296
10.5	77	154	8.75	69	190	6.685	86	216	5.775	77	296	2.8	86	360
9	77	172	7.5	68	232	5.73	86	248	4.95	76	344	2.4	79	456
7.8	75	208	6.5	68	264	4.966	85	280	4.29	75	408	2.08	72	568
7.2	74	226	6	67	296	4.584	85	312	3.96	75	440	1.92	69	648
6.6	73	244	5.5	67	312	4.202	85	328	3.63	74	488	1.76	64	760
6	72	280	5	66	360	3.82	85	376	3.3	73	536	1.6	59	904
5.4	71	316	4.5	66	392	3.438	85	408	2.97	73	600	*	*	*
4.8	70	352	4	65	456	3.056	84	472	2.64	72	696	*	*	*
4.2	68	406	3.5	64	520	2.674	84	536	2.31	71	792	*	*	*
3	64	622	2.5	61	760	1.91	82	776	*	*	*	*	*	*

*RE fell below 90%

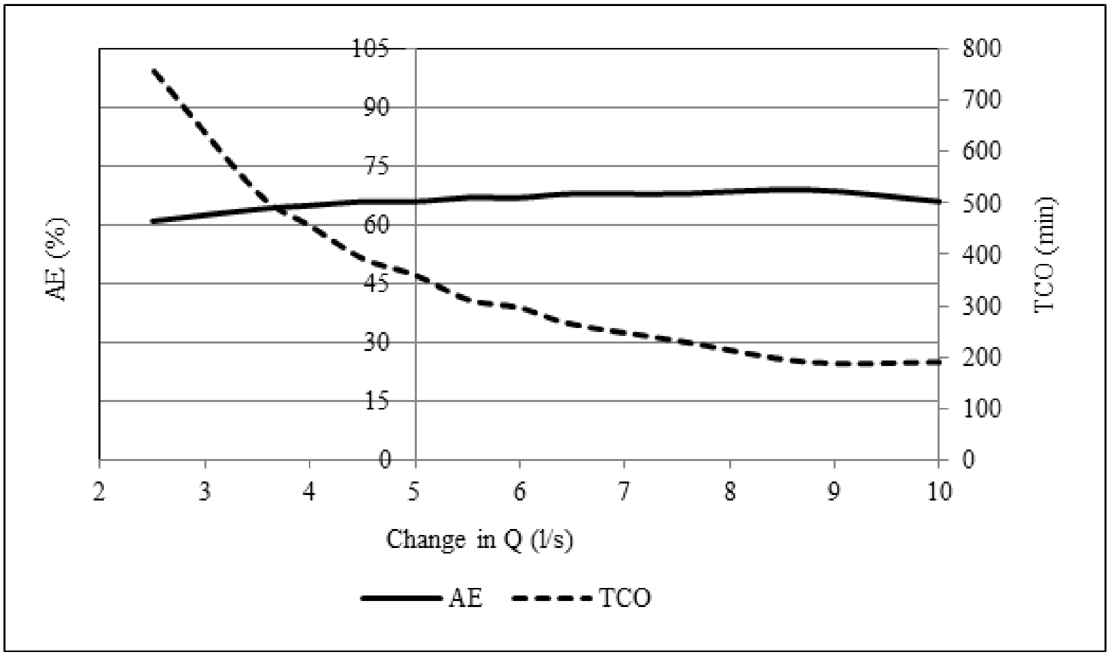


Figure C.9: Effect of varied flow on AE and TCO (scaled infiltration - Trial 2A)

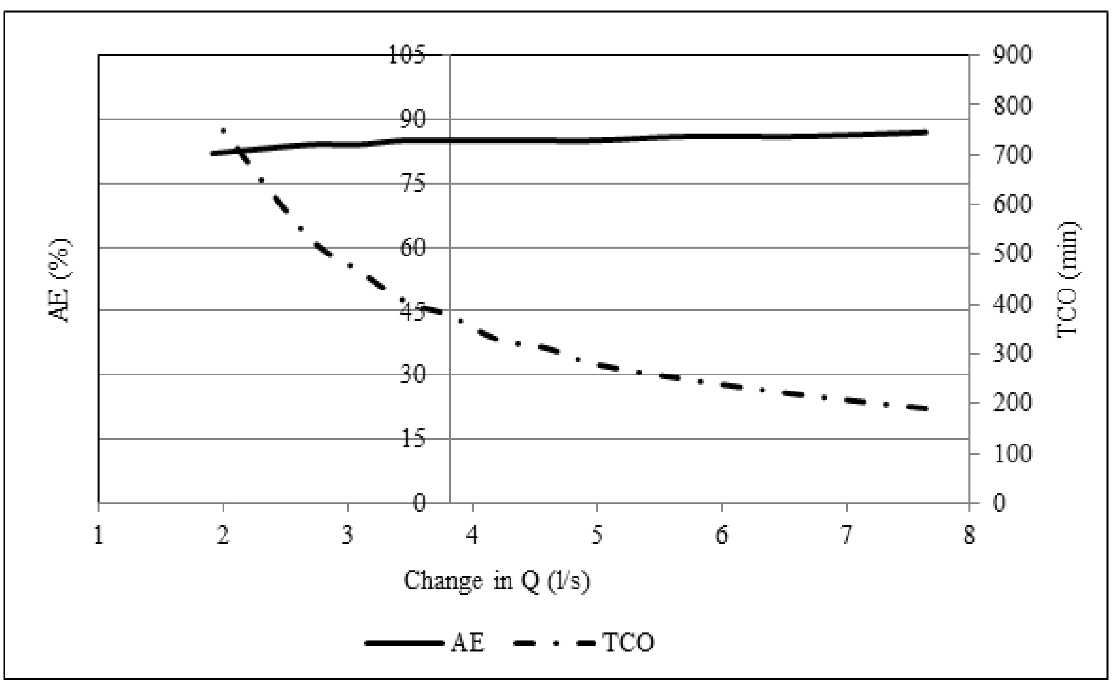


Figure C.10: Effect of varied flow on AE and TCO (scaled infiltration - Trial 3A)

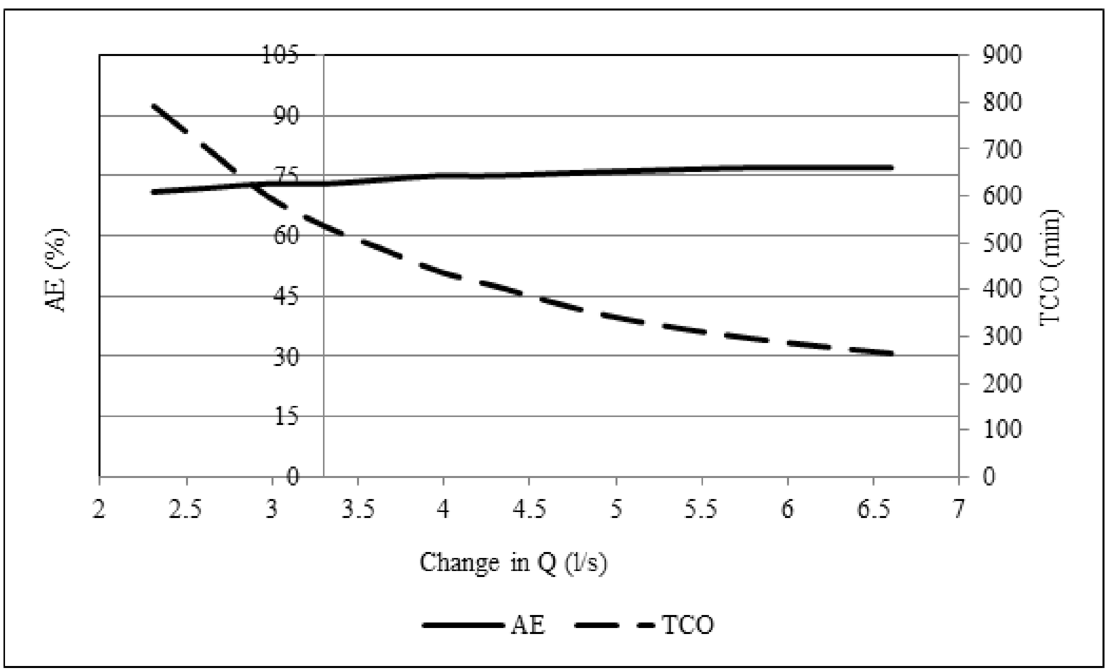


Figure C.11: Effect of varied flow on AE and TCO (scaled infiltration - Trial 4A)

C.2 Varying the irrigation deficit

The effect on (irrigation performance) of varying the irrigation deficit is illustrated in the figures and table below:

Table C.7: Effect of varied Q on AE and TCO (Optimisation system)

	Site A								Site B	
Change in	Trial 1A		Trial 2A		Trial 3A		Trial 4A		Trial 2B	
deficit (%)	AE (%)	TCO (min)	AE (%)	TCO (min)	AE (%)	TCO (min)	AE (%)	TCO (min)	AE (%)	TCO (min)
50	99	298	98	360	*	*	100	600	81	984
30	92	280	86	360	100	408	94	552	73	952
20	86	280	80	360	100	376	88	536	69	936
10	79	280	73	360	93	376	81	536	64	920
0	72	280	66	360	85	376	73	536	59	904
-10	65	280	60	360	77	376	66	536	54	888
-20	57	280	53	360	68	376	59	536	49	872
-30	50	280	46	360	59	376	51	536	43	872
-50	36	280	33	360	43	376	37	536	31	856

*RE fell below 90%

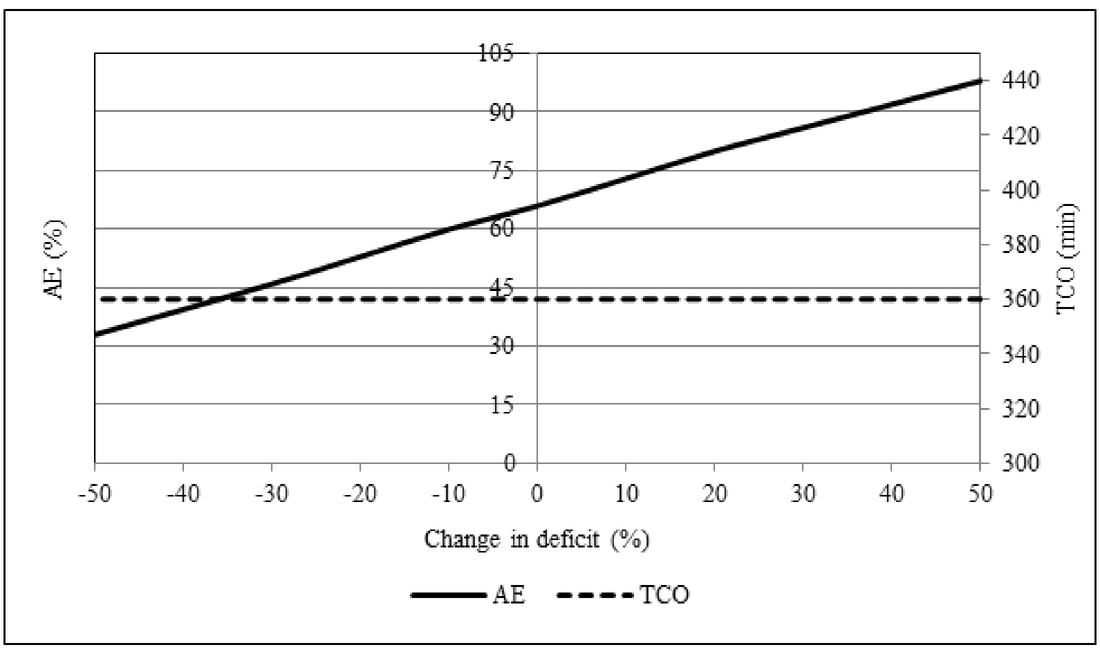


Figure C.12: Effect of varied deficit on AE and TCO (optimisation system Trial 2A)

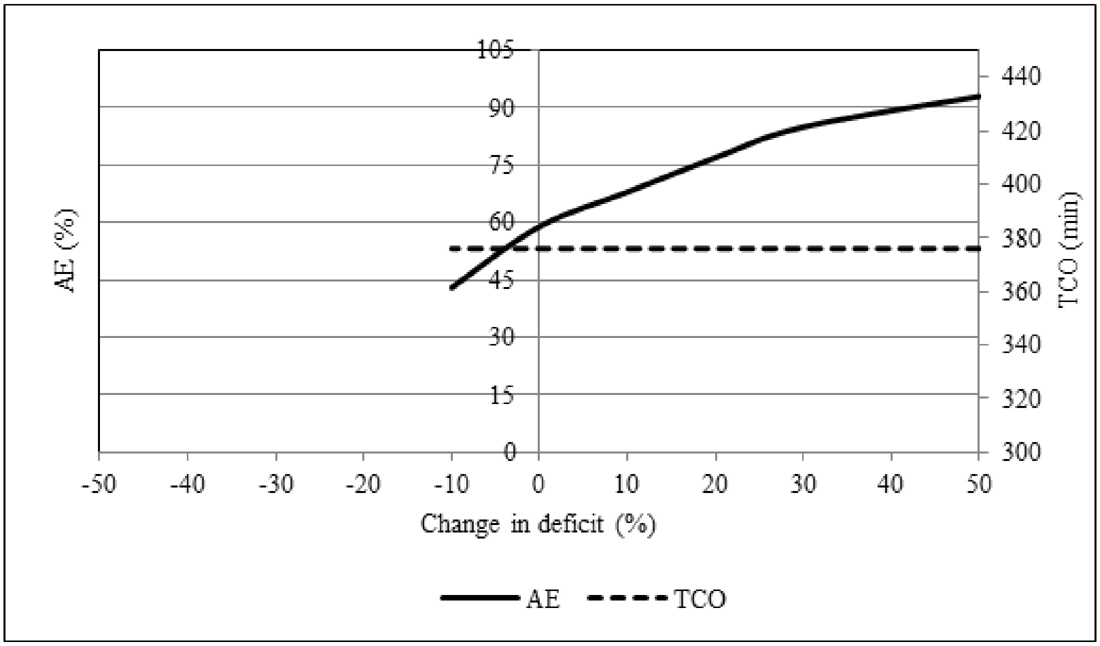


Figure C.13: Effect of varied deficit on AE and TCO (optimisation system Trial 3A)

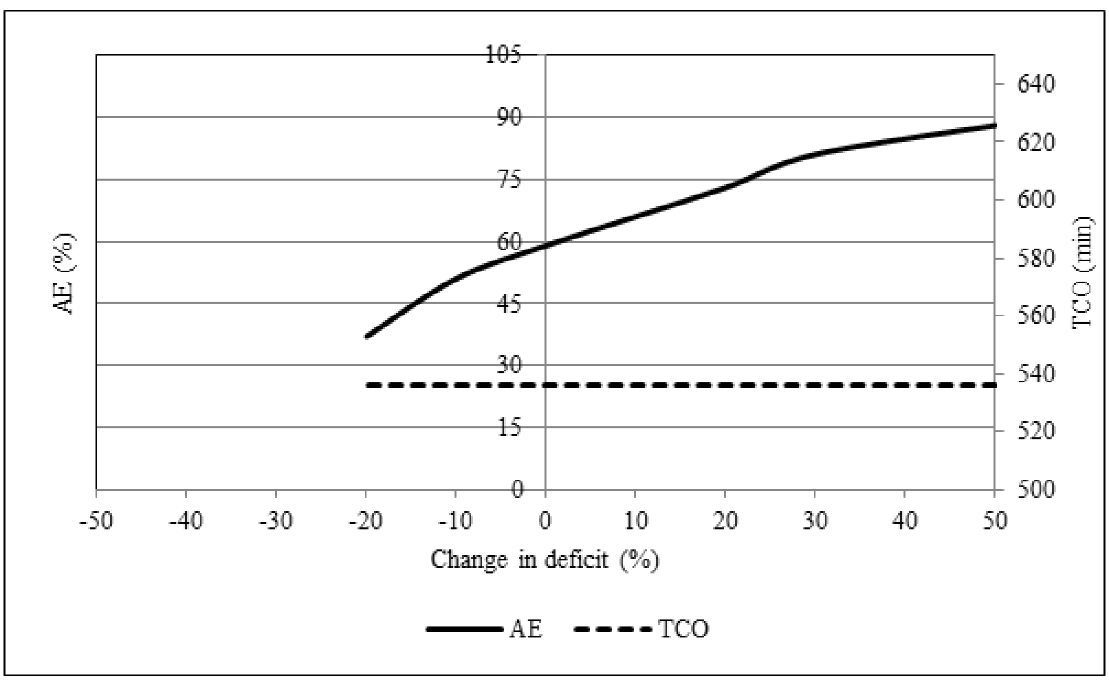


Figure C.14: Effect of varied deficit on AE and TCO (optimisation system Trial 4A)

Table C.8: Effect of varied Q on AE and TCO (Optimisation system)

	Site A								Site B	
Change in	Trial 1A		Trial 2A		Trial 3A		Trial 4A		Trial 2B	
deficit (%)	AE (%)	RE (%)	AE (%)	RE (%)	AE (%)	RE (%)	AE (%)	RE (%)	AE (%)	RE (%)
50	100	86	98	99	100	79	100	87	87	81
30	92	92	86	100	100	91	94	94	78	83
20	86	93	79	100	99	99	87	95	73	84
10	79	93	72	100	92	100	80	95	67	85
0	72	93	66	100	84	100	73	95	62	86
-10	65	93	59	100	76	100	66	95	56	86
-20	57	93	53	100	68	100	58	95	50	87
-30	50	93	46	100	58	100	51	95	44	88
-50	36	93	33	100	42	100	37	95	32	88

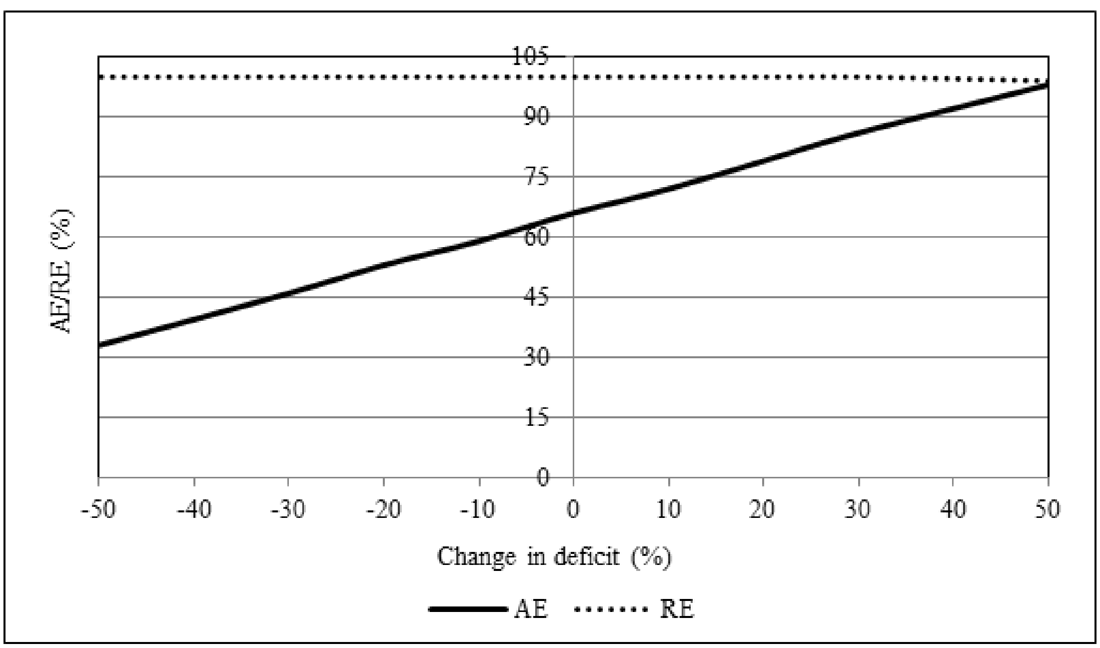


Figure C.15: Effect of varied deficit on AE and RE (optimisation system -Trial 2A

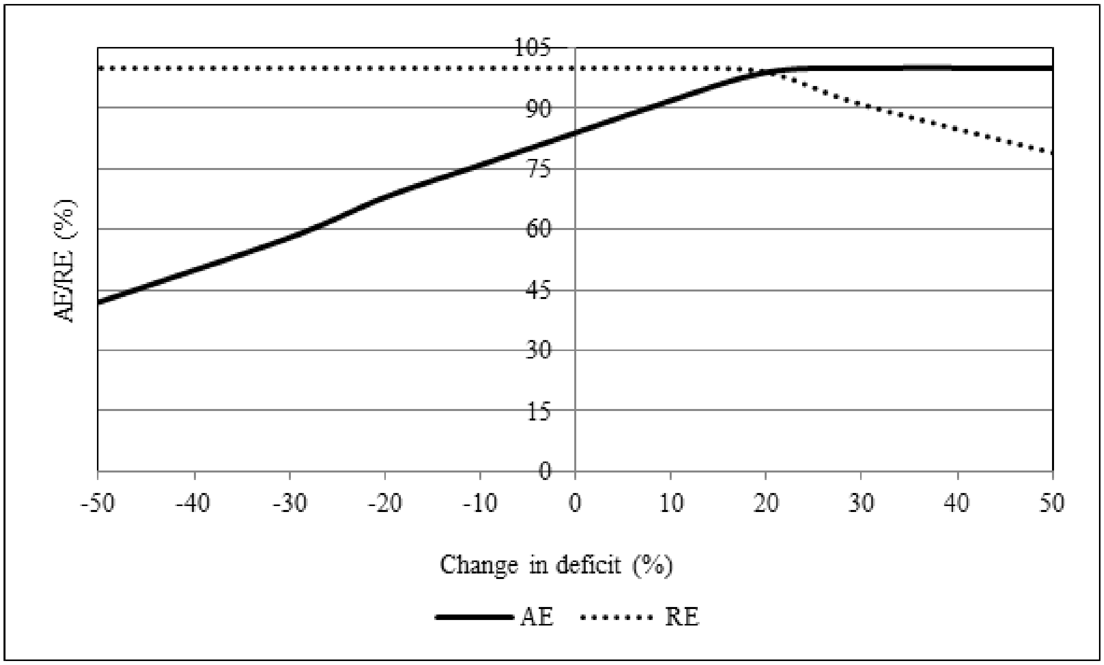


Figure C.16: Effect of varied deficit on AE and RE (optimisation system -Trial 3A)

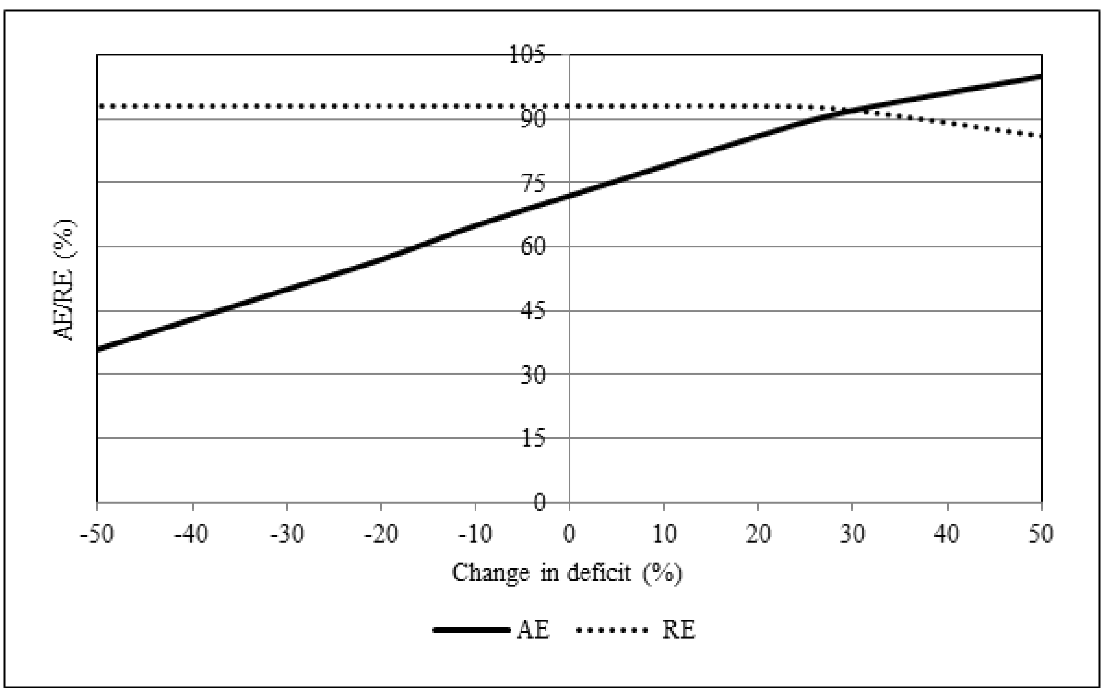


Figure C.17: Effect of varied deficit on AE and RE (optimisation system -Trial 4A)

C.3 Infiltration scaling process

The following graphs show the model, actual and scaled infiltration curves.

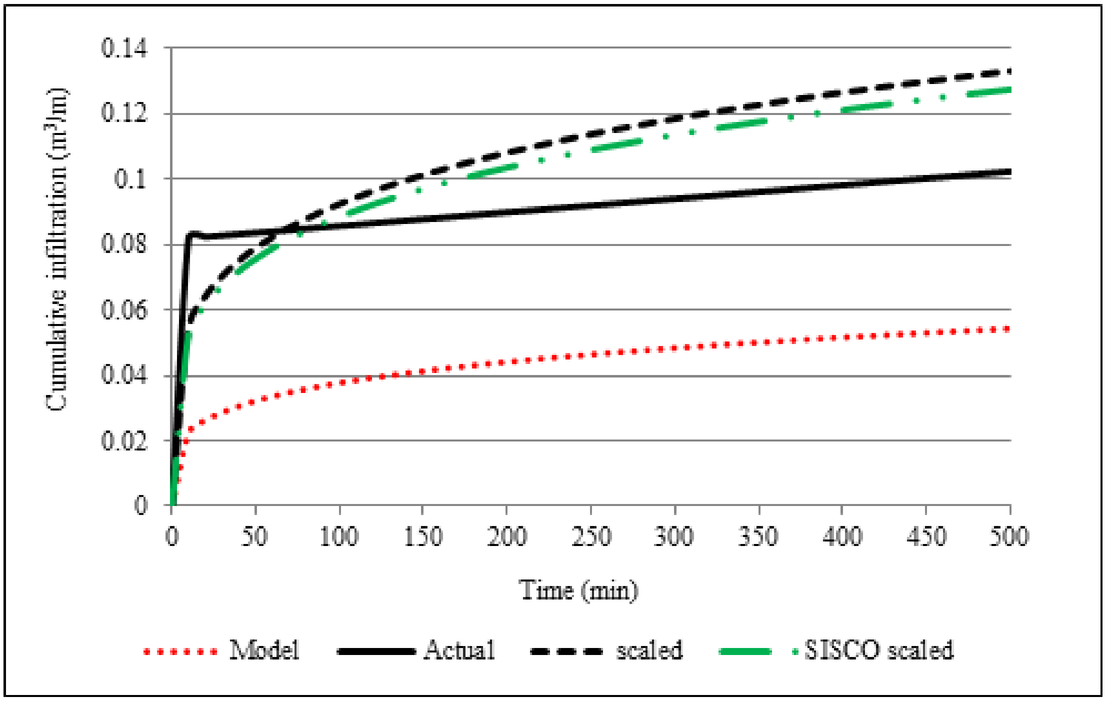


Figure C.18: Model, actual and scaled infiltration curves (Trial 1A)

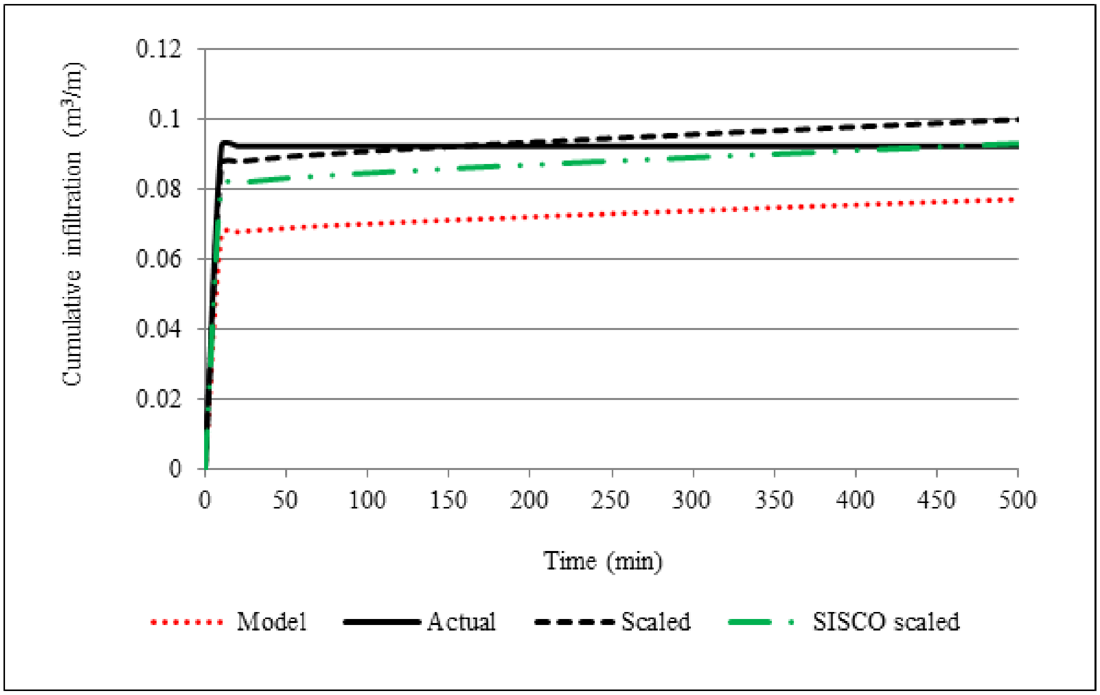


Figure C.19: Model, actual and scaled infiltration curves (Trial 3A)

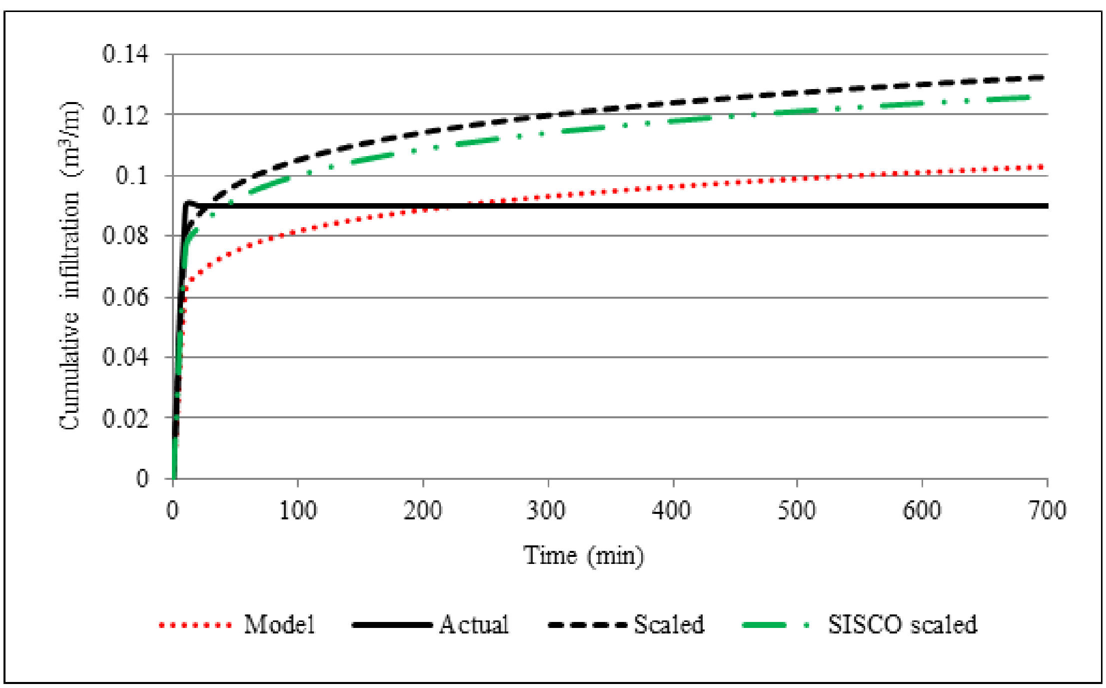


Figure C.20: Model, actual and scaled infiltration curves (Trial 4A)

C.4 Comparison of advance curves

The following graphs show advance curves predicted from the scaled parameters (Pre), measured or actual (Act) and produced by SISCO using the actual infiltration (Act infil).

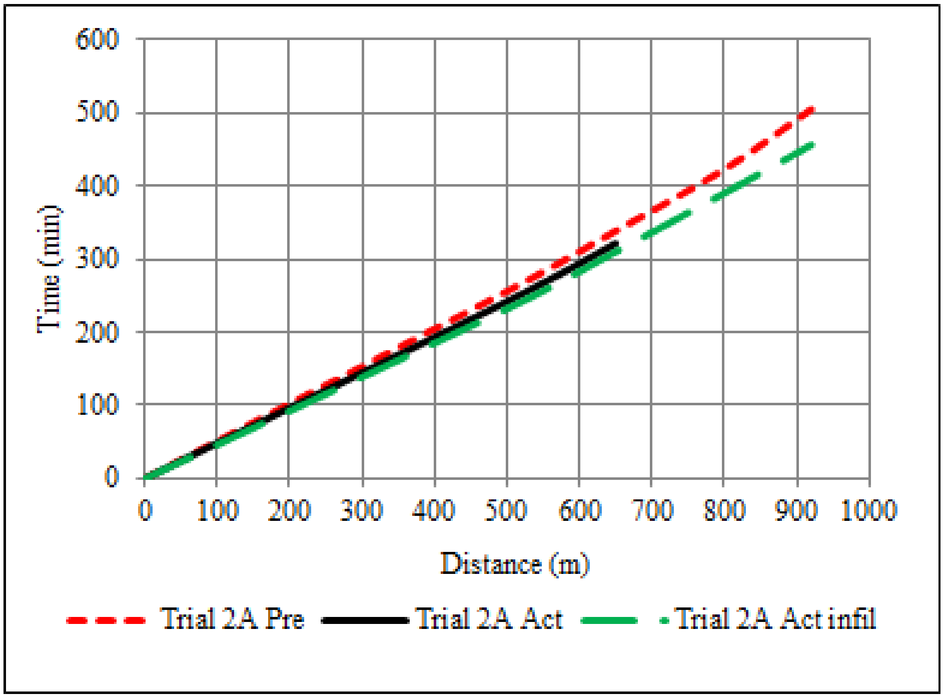


Figure C.21: Actual and predicted advance curves - Trial 2A

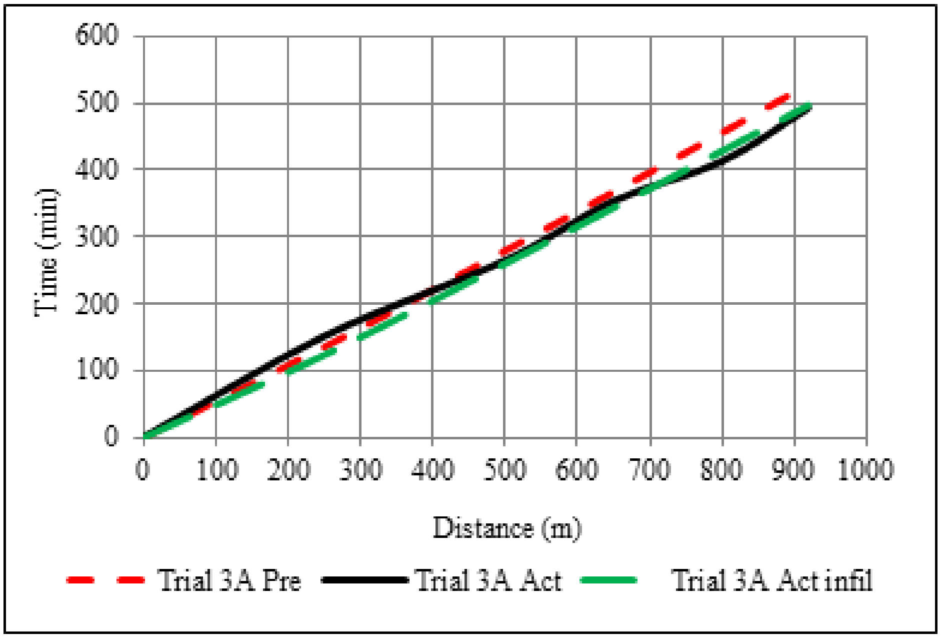


Figure C.22: Actual and predicted advance curves - Trial 3A

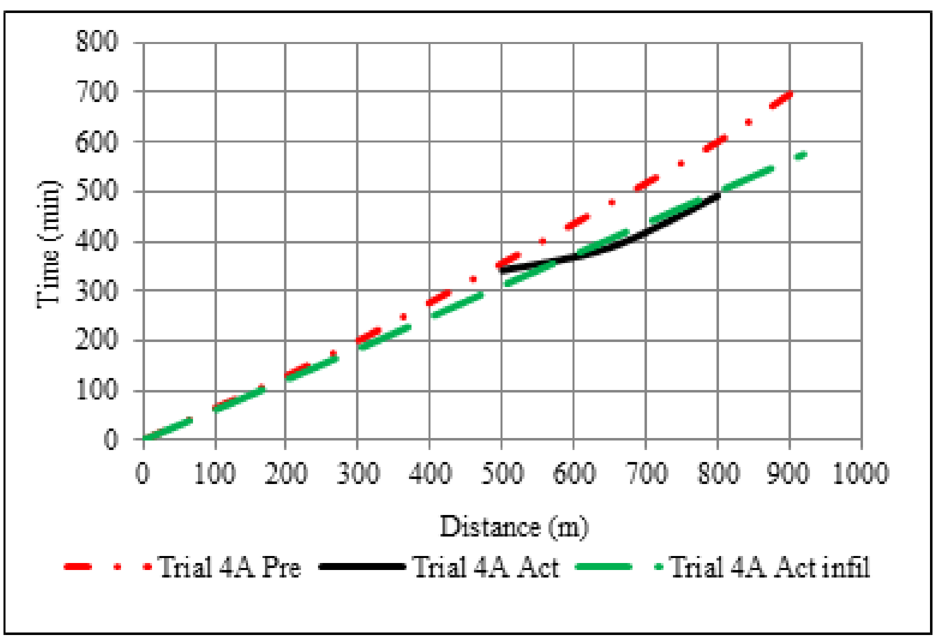


Figure C.23: Actual and predicted advance curves - Trial 4A

C.5 Selection of the advance point

Table C.9: Effect of advance distance on the scaling factor - Trial 2A

Trial 2A model curve values			
a	1.00E-07		
k	0.081503		
f_o	4.16E-05		
r	0.97273		
A_o (m^2)	0.04600		
σ_y	0.77		
σ_z	1		
Q_o (l/s)	5		
	Scaling process		
Q_ot (m^3)	73.515	96.30	132.6
Advance distance, x, (m)	500	650	920
Advance time, t, (min)	245.05	321	442
Scaling factor (F)	1.288	1.277	1.197
	Scaled infiltration parameters		
a	1.0E-07	1.0E-07	1.0E-07
k	0.10496	0.10410	0.09756
f_o	5.35E-05	5.31E-05	4.98E-05

Table C.10: Effect of advance distance on the predicted advance curves - Trial 2A

		Advance distance (m)		
		500	650	920
Distance (m)	Actual advance time (min)	Predicted advance times (min)		
0	0	0	0	0
500	242	256	254	242
650	321	338	336	320
800		423	420	399
920	442	505	499	465

Table C.11: Effect of advance distance on the performance of the optimisation system - Trial 2A

Optimisation strategy			
DU ≥	95(93[1])		
RE ≥	95		
AE ≥	57		
	Advance distance (m)		
	500	650	920
Predicted Performance (%)			
AE	66	66	71
AE (with 90% recycling)	66	66	71
DU	94	95	95
RE	100	100	100
Inflow volume (m^3)	118	118	110
Drainage (%)	34	33	29
Runoff (%)	0	0.54	0.38
Time to cut off (min)	392	392	360

[1]No optimum solution found at advance distance of 500 m, DU reduced to 93%

Table C.12: Effect of advance distance on the scaling factor - Trial 3A

Trial 3A model curve values					
a	0.01095				
k	0.06536				
f_o	1.44E-05				
r	0.97565				
A_o (m^2)	0.03913				
σ_y	0.77				
σ_z	0.98930				
Q_o (l/s)	3.82				
	Scaling process				
Q_ot (m^3)	34.84	60.82	81.14	94.66	113.00
Advance distance, x, (m)	250	500	650	800	920
Advance time, t, (min)	152	265.36	354	413	493
Scaling factor (F)	1.573	1.295	1.324	1.224	1.273
	Scaled infiltration parameters				
a	0.01095	0.01095	0.01095	0.01095	0.01095
k	0.10283	0.08464	0.08652	0.07997	0.08322
f_o	2.27E-05	1.86E-05	1.91E-05	1.76E-05	1.83E-05

Table C.13: Effect of advance distance on the predicted advance curves - Trial 3A

		Advance distance (m)				
		250	500	650	800	920
Distance (m)	Actual advance time (min)	Predicted advance times (min)				
0	1	0	0	0	0	0
250	152	157	136	138	130	134
500	265	324	279	284	268	276
650	354	426	367	373	352	363
800	413	532	456	464	438	450
920	493		528	538	506	522

Table C.14: Effect of advance distance on the performance of the optimisation system - Trial 3A

Optimisation strategy					
DU $\geq$	90				
RE $\geq$	95				
AE $\geq$	80				
	Advance distance (m)				
	250	500	650	800	920
Predicted Performance (%)					
AE		83	83	89	86
AE (with 90% recycling)		83	83	89	86
DU		90	92	92	92
RE		98	98	98	98
Inflow volume (m^3)		94	95	87	91
Drainage (%)		15	17	10	14
Runoff (%)		0	0	0	0
Time to cut off (min)		408	408	376	392

Table C.15: Effect of advance distance on the scaling factor - Trial 4A

Trial 4A model curve values			
a	0.118829		
k	0.047324		
f_o	0		
r	1.06037		
A_o (m^2)	0.03481		
σ_y	0.77		
σ_z	0.89068		
Q_o (l/s)	3.3		
	Scaling process		
Q_ot (m^3)	67.64	76.82	97.42
Advance distance, x, (m)	500	650	800
Advance time, t, (min)	341.64	388	492
Scaling factor (F)	1.287	1.068	1.079
	Scaled infiltration parameters		
a	0.11883	0.11883	0.11883
k	0.06090	0.05053	0.05105
f_o	0	0	0

Table C.16: Effect of advance distance on the predicted advance curves - Trial 4A

		Advance distance (m)		
		500	650	800
Distance (m)	Actual advance time (min)	Predicted advance times (min)		
0	0	0	0	0
250		164	141	142
500	342	356	305	307
650	388	477	408	411
800	492	601	513	517
920		716	598	604

Table C.17: Effect of advance distance on the performance of the optimisation system - Trial 4A

Optimisation strategy			
DU $\geq$	69		
RE $\geq$	90		
AE $\geq$	70		
	Advance distance (m)		
	500	650	800
Predicted Performance (%)			
AE	73	89	88
AE (with 90% recycling)	73	89	88
DU	73	72	69
RE	94	93	92
Inflow volume (m^3)	112	91	91
Drainage (%)	27	11	12
Runoff (%)	0	0	0
Time to cut off (min)	568	456	456

Table C.18: Effect of advance distance on the scaling factor - Trial 2B

Trial 2B model curve values					
a	0.51051				
k	0.00494				
f_o	0				
r	0.55481				
A_o (m^2)	0.01999				
σ_y	0.77				
σ_z	0.75880				
Q_o (l/s)	1.6				
	Scaling process				
Q_ot (m^3)	11.52	37.96	51.65	64.51	72.48
Advance distance, x, (m)	200	400	500	600	650
Advance time, t, (min)	120	395.46	538	672	755
Scaling factor (F)	0.978	1.002	0.947	0.886	0.871
	Scaled infiltration parameters				
a	0.51051	0.51051	0.51051	0.51051	0.51051
k	0.00483	0.00495	0.00468	0.00437	0.00430
f_o	0	0	0	0	0

Table C.19: Effect of advance distance on the predicted advance curves - Trial 2B

		Advance distance (m)				
		200	400	500	600	650
Distance (m)	Actual advance time (min)	Predicted advance times (min)				
0	0	0	0	0	0	0
200		112	116	108	100	98
400	342	372	386	354	320	312
500	388	557	580	529	476	464
600	492	781	814	739	663	645
650		906	945	858	768	746

Table C.20: Effect of advance distance on the performance of the optimisation system - Trial 2B

Optimisation strategy					
DU $\geq$	30				
RE $\geq$	85				
AE $\geq$	58				
	Advance distance (m)				
	200	400	500	600	650
Predicted Performance (%)					
AE	65	62	68	75	77
AE (with 90% recycling)	65	62	68	75	77
DU	30	31	32	37	38
RE	85	85	85	85	85
Inflow volume (m^3)	75	79	71	65	64
Drainage (%)	35	38	32	25	24
Runoff (%)	0	0	0	0	0
Time to cut off (min)	776	824	744	680	664

C.6 Selection of the model curve

Note: Kostiakov-Lewis equation (Eqn. 2.4) used to compute cumulative infiltration.

Table C.21: Cumulative infiltration for model and average (parameters and shape) curves in relation to the rest of the curves (Trial 1A)

	Furrow Number								Average	
	F1	F2	F3	F4	F5	F6	F7	F8	para	shape
a	0.04454	0.25021	0	0	1E-07	0.27418	0.27893	0.2161	0.1330	0.1174
k	0.04718	0.0204	0.0896	0.0811	0.08150	0.01558	0.01386	0.01122	0.04505	0.03714
f_o	0.00012	0	0	0	4.16E-05	0 0.0001	0 3.31E-05	3.31E-05		
Time (min)	Cumulative infiltration (m^3/m)									
0	0	0	0	0	0	0	0	0	0	0
20	0.0563	0.0431	0.0896	0.0811	0.0823	0.0354	0.0340	0.0214	0.0678	0.0535
40	0.0604	0.0512	0.0896	0.0811	0.0832	0.0428	0.0429	0.0249	0.0749	0.0586
60	0.0639	0.0567	0.0896	0.0811	0.0840	0.0479	0.0495	0.0272	0.0796	0.0620
80	0.0670	0.0610	0.0896	0.0811	0.0848	0.0518	0.0552	0.0289	0.0833	0.0648
100	0.0700	0.0645	0.0896	0.0811	0.0857	0.0551	0.0603	0.0304	0.0864	0.0671
120	0.0729	0.0675	0.0896	0.0811	0.0865	0.0579	0.0649	0.0316	0.0891	0.0691
140	0.0758	0.0701	0.0896	0.0811	0.0873	0.0604	0.0693	0.0326	0.0916	0.0710
160	0.0785	0.0725	0.0896	0.0811	0.0882	0.0627	0.0734	0.0336	0.0938	0.0727
180	0.0813	0.0747	0.0896	0.0811	0.0890	0.0647	0.0773	0.0345	0.0958	0.0743
200	0.0840	0.0767	0.0896	0.0811	0.0898	0.0666	0.0811	0.0353	0.0978	0.0758
220	0.0866	0.0785	0.0896	0.0811	0.0906	0.0684	0.0848	0.0360	0.0996	0.0772
240	0.0893	0.0802	0.0896	0.0811	0.0915	0.0700	0.0884	0.0367	0.1013	0.0786
260	0.0919	0.0819	0.0896	0.0811	0.0923	0.0716	0.0918	0.0373	0.1030	0.0799
280	0.0946	0.0834	0.0896	0.0811	0.0931	0.0731	0.0952	0.0379	0.1046	0.0812
300	0.0972	0.0848	0.0896	0.0811	0.0940	0.0744	0.0986	0.0385	0.1061	0.0825
320	0.0998	0.0862	0.0896	0.0811	0.0948	0.0758	0.1019	0.0390	0.1076	0.0837
340	0.1023	0.0875	0.0896	0.0811	0.0956	0.0770	0.1051	0.0396	0.1091	0.0849
360	0.1049	0.0888	0.0896	0.0811	0.0965	0.0783	0.1082	0.0400	0.1105	0.0860
380	0.1075	0.0900	0.0896	0.0811	0.0973	0.0794	0.1114	0.0405	0.1118	0.0871
400	0.1101	0.0912	0.0896	0.0811	0.0981	0.0806	0.1145	0.0410	0.1132	0.0883
420	0.1126	0.0923	0.0896	0.0811	0.0990	0.0816	0.1175	0.0414	0.1145	0.0894
440	0.1152	0.0934	0.0896	0.0811	0.0998	0.0827	0.1205	0.0418	0.1158	0.0904
460	0.1177	0.0944	0.0896	0.0811	0.1006	0.0837	0.1235	0.0422	0.1170	0.0915
480	0.1203	0.0954	0.0896	0.0811	0.1015	0.0847	0.1264	0.0426	0.1183	0.0925
500	0.1228	0.0964	0.0896	0.0811	0.1023	0.0856	0.1294	0.0430	0.1195	0.0936

C.7 Complete set of results from multi-furrow evaluation

The complete sets of results of the multi-furrow evaluation performed in Chapter 6 are presented below. Note: Model and wheel-tracked furrows are shaded in black and gray respectively.

Table C.22: Trial 1A

	Performance measure						
	AE (%)	RE (%)	DU (%)	AE recy (%)	Runoff (%)	Drain. (%)	Inflow (m^3)
Trial furrow Furrow 5	50.8	100.0	99.6	87.3	46.4	2.6	152.6
Entire set (8 furrows)	48.0	94.4	71.2	79.4	44.0	7.9	1221.2
Individual results							
Furrow no.							
1	50.8	100.0	91.4	69.7	30.0	19.0	152.6
2	50.8	100.0	97.2	79.7	40.2	8.9	152.6
3	50.8	100.0	99.9	82.7	42.8	6.2	152.6
4	50.8	100.0	99.9	89.7	48.2	0.8	152.6
5	50.8	100.0	99.6	87.3	46.4	2.6	152.6
6	50.8	100.0	97.9	87.3	46.5	2.6	152.7
7	50.8	100.0	90.4	66.3	25.9	23.2	152.6
8	27.9	54.9	98.3	79.4	72.0	0.0	152.6

Table C.23: Trial 1B

	Performance measure						
	AE (%)	RE (%)	DU (%)	AE recy (%)	Runoff (%)	Drain. (%)	Inflow (m^3)
Trial furrow Furrow 4	57.1	89.1	39.0	57.1	0.0	42.8	89.1
Entire set (8 furrows)	54.5	85.0	28.1	56.3	3.6	41.8	712.8
Individual results							
Furrow no.							
1	51.5	80.4	13.9	51.5	0.0	48.4	89.1
2	55.4	86.4	31.0	55.4	0.0	44.5	89.1
3	53.2	83.0	20.9	53.2	0.0	46.8	89.1
4	57.1	89.1	39.0	57.1	0.0	42.8	89.1
5	51.2	79.9	13.1	51.2	0.0	48.7	89.1
6	52.5	81.9	18.3	52.5	0.0	47.4	89.1
7	51.1	79.8	12.3	51.1	0.0	48.8	89.1
8	64.1	100.0	99.9	86.7	28.9	6.9	89.1

Table C.24: Trial 2A

	Performance measure						
	AE (%)	RE (%)	DU (%)	AE recy (%)	Runoff (%)	Drain. (%)	Inflow (m^3)
Trial furrow Furrow 5	65.2	100.0	95.4	69.4	6.7	28.0	119.1
Entire set (8 furrows)	60.5	92.1	68.2	77.6	24.5	14.9	945.3
Individual results							
Furrow no.							
1	51.2	77.5	99.8	91.0	48.7	0.0	117.6
2	52.2	79.1	99.7	91.4	47.6	0.0	117.6
3	65.2	100.0	96.4	72.1	10.7	24.0	119.1
4	65.2	100.0	99.9	76.7	16.7	18.0	119.1
5	65.2	100.0	95.4	69.4	6.7	28.0	119.1
6	53.4	80.9	99.8	91.7	46.5	0.0	117.6
7	65.7	99.6	77.1	68.8	5.1	29.1	117.6
8	66.0	100.0	86.0	75.7	14.3	19.6	117.6

Table C.25: Trial 2B

	Performance measure						
	AE (%)	RE (%)	DU (%)	AE recy (%)	Runoff (%)	Drain. (%)	Inflow (m^3)
Trial furrow Furrow 4	63.6	100.0	81.0	67.6	6.6	29.8	89.9
Entire set (8 furrows)	60.2	94.8	66.5	73.2	19.8	20.0	719.8
Individual results							
Furrow no.							
1	63.6	100.0	84.2	73.7	15.2	21.2	89.9
2	61.7	97.6	72.7	61.7	0.0	38.2	90.3
3	63.6	100.0	94.5	81.1	24.0	12.5	89.9
4	63.6	100.0	81.0	67.6	6.6	29.8	89.9
5	63.2	100.0	79.0	64.9	2.9	33.8	90.3
6	63.6	100.0	92.9	80.8	23.7	12.6	89.9
7	63.6	100.0	93.1	81.8	24.7	11.6	89.9
8	38.6	60.8	99.7	86.2	61.3	0.0	89.9

Table C.26: Trial 3A

	Performance measure						
	AE (%)	RE (%)	DU (%)	AE recy (%)	Runoff (%)	Drain. (%)	Inflow (m^3)
Trial furrow Furrow 2	76.0	100.0	98.5	87.2	14.2	9.4	104.5
Entire set (8 furrows)	74.76	98.26	84.89	87.7	16.44	8.65	836.39
Individual results							
Furrow no.							
1	76.1	100.0	96.4	88.2	15.2	8.6	104.5
2	76.0	100.0	98.5	87.2	14.2	9.4	104.5
3	76.1	100.0	99.8	82.2	8.4	15.4	104.6
4	76.1	100.0	97.6	82.7	8.9	14.9	104.5
5	76.1	100.0	97.9	83.9	10.3	13.5	104.5
6	70.5	92.6	97.6	95.8	29.4	0.0	104.5
7	75.7	99.6	91.0	89.2	16.8	7.2	104.6
8	71.5	93.9	90.2	96.0	28.4	0.1	104.5

Table C.27: Trial 3B

	Performance measure						
	AE (%)	RE (%)	DU (%)	AE recy (%)	Runoff (%)	Drain. (%)	Inflow (m^3)
Trial furrow Furrow 2	82.2	99.7	90.2	88.2	7.6	10.2	69.3
Entire set (8 furrows)	80.9	97.7	83.6	88.8	9.8	9.1	551.7
Individual results							
Furrow no.							
1	81.7	98.5	87.9	90.8	11.1	7.1	68.9
2	82.2	99.7	90.2	88.2	7.6	10.2	69.3
3	80.3	96.8	89.4	95.0	17.2	2.4	68.8
4	83.0	100.0	95.2	90.3	9.0	7.9	68.9
5	82.6	99.5	88.0	86.7	5.3	12.0	68.8
6	83.0	100.0	98.5	91.2	10.1	6.8	68.9
7	73.5	89.2	46.7	73.5	0.0	26.4	69.3
8	81.3	98.0	96.5	97.5	18.4	0.2	68.8

Table C.28: Trial 4A

	Performance measure						
	AE (%)	RE (%)	DU (%)	AE recy (%)	Runoff (%)	Drain. (%)	Inflow (m^3)
Trial furrow Furrow 2	75.5	100.0	99.9	96.5	24.2	0.2	115.7
Entire set (8 furrows)	67.5	89.6	62.7	89.4	27.2	5.1	926.2
Individual results							
Furrow no.							
1	75.3	99.8	90.6	88.2	16.3	8.3	115.7
2	75.5	100.0	99.9	96.5	24.2	0.2	115.7
3	74.9	100.0	94.6	85.4	13.7	11.3	116.6
4	73.7	97.7	99.9	96.4	26.1	0.0	115.7
5	75.4	99.9	90.0	85.2	12.7	11.8	115.6
6	74.2	98.3	84.1	86.9	16.3	9.4	115.6
7	39.8	52.7	99.8	86.6	60.1	0.0	115.6
8	51.5	68.1	96.1	91.2	48.5	0.0	115.6

Table C.29: Trial 4B

	Performance measure						
	AE (%)	RE (%)	DU (%)	AE recy (%)	Runoff (%)	Drain. (%)	Inflow (m^3)
Trial furrow Furrow 2	62.6	93.9	99.1	94.2	37.3	0.0	96.4
Entire set (8 furrows)	58.7	88.0	43.4	70.1	18.1	23.0	771.2
Individual results							
Furrow no.							
1	32.2	48.3	99.7	82.4	67.7	0.0	96.4
2	62.6	93.9	99.1	94.2	37.3	0.0	96.4
3	66.7	100.0	84.7	73.3	10.1	23.1	96.4
4	66.7	100.0	98.0	85.7	24.7	8.5	96.4
5	66.7	100.0	86.6	70.1	5.4	27.8	96.4
6	58.1	87.3	39.6	58.1	0.0	41.7	96.4
7	56.5	84.8	30.5	56.5	0.0	43.2	96.4
8	59.8	89.8	55.8	59.8	0.0	39.8	96.4

Appendix D

Final Field Trials (2011/12 irrigation season)

The complete data for the trials undertaken during the 2011/12 irrigation season are shown in this appendix. The data has been used in Chapter 7. The infiltration parameters a, k, f_o and p, r, A_o were determined using the SISCO and IPARM models respectively.

D.0.1 Trial 1C

Date: 7/01/2012

Field length: 975 m

Slope: 0.00081 m/m

Inflow: 3.83 l/s

Furrow spacing: 1 m

Deficit: 80 mm

Table D.1: Furrow dimensions - Trial 1C

Top width	800 mm
Middle width	550 mm
Bottom width	300 mm
Total depth	160 mm

Table D.2: Advance data - Trial 1C

	Furrow number							
	1	2	3	4	5	6	7	8
Distance (m)	Advance time (mins)							
0	0	0	0	0	0	0	0	0
250	39	109	136	130	83	100	97	99
500	100	233	278	279	195	213	209	205
800	190	368	438	459	383	383	351	320
900	222	421	496	548	439	443	399	366

Table D.3: Infiltration parameters - Trial 1C

	F1	F2	F3	F4	F5	F6	F7	F8
a	0.604510154	0.021073374	0	0.013024061	0.283958053	0.090415365	0.107812789	0
k	0.001702282	0.06546182	0.092032895	0.0798029	0.015798965	0.039490203	0.039259231	0.058662634
f_o	0	0	0	7.02668E-05	4.87938E-05	8.4128E-05	7.07935E-06	0
p	16.84015	2.59746	1.80065	3.40945	9.52097	5.51085	3.94037	2.52614
r	0.73618	0.9683	1.00153	0.88657	0.74684	0.83682	0.90673	0.99628
A_o	0.03566	0.03566	0.03566	0.03566	0.03566	0.03566	0.03566	0.03566

D.0.2 Trial 1D

Date: 19/1/2012

Field length: 600 m

Slope: 0.0008 m/m

Furrow spacing: 2 m

Deficit: 80 mm

Table D.4: Furrow dimensions - Trial 1D

Top width	800 mm
Middle width	650 mm
Bottom width	500 mm
Total depth	105 mm

Table D.5: Advance data - Trial 1D

	Furrow number			
	1	2	3	4
Discharge (l/s)	2.8	2.4	2.4	2.8
Distance (m)	Advance time (mins)			
0	0	0	0	0
100	118	123	123	123
200	256	261	263	263
300	393	398	399	404
400	527	513	514	517
500	670	654	657	662
580	792	785		796

Table D.6: Infiltration parameters - Trial 1D

	F1	F2	F3	F4
a	0.039072184	0	0	0
k	0.169474513	0.167744519	0.175673693	0.203283423
f_o	2.53894E-05	3.43462E-05	0	4.56597E-05
p	1.1272	0.9859	0.81245	1.0067
r	0.93592	0.95862	0.99038	0.95355
A_o	0.03335	0.02967	0.02967	0.03335
Flow rate (l/s)	3.1	2.6	2.6	3.1

D.0.3 Trial 2D

Date: 17/2/2012

Field length: 600 m

Slope: 0.0008 m/m

Furrow spacing: 2 m

Deficit: 80 mm

Table D.7: Furrow dimensions - Trial 2D

Top width	800 mm
Middle width	650 mm
Bottom width	500 mm
Total depth	105 mm

Table D.8: Advance data - Trial 2D

	Furrow number			
	1	2	3	4
Discharge (l/s)	2.8	2.4	2.4	2.8
Distance (m)	Advance time (mins)			
0	0	0	0	0
100	138	131	129	130
200	292	288	284	284
300	449	441	435	440
400	606	585	580	580
500	755	750	745	

Table D.9: Infiltration parameters - Trial 2D

	F1	F2	F3	F4
a	0.035408536	0.054313278	0.062928617	0.046381587
k	0.184450232	0.138940811	0.131317787	0.168423745
f_o	0	0	0	0
p	0.85408	0.95844	1.01249	0.94086
r	0.96082	0.94543	0.93815	0.94982
A_o	0.03117	0.02814	0.02814	0.03117
Flow rate (l/s)	2.8	2.4	2.4	2.8

D.1 Selection of the advance distance

D.1.1 Trial 1C

Table D.10: Effect of advance distance on the scaling factor - Trial 1C

Trial 1C model curve values				
a	0.077			
k	0.04731			
f_o	1.40E-05			
r	0.96806			
A_o (m^2)	0.03569			
σ_y	0.77			
σ_z	0.9296			
Q_o (l/s)	3.83			
	Scaling process			
Q_ot (m^3)	29.87	64.28	105.48	125.93
Advance distance, x, (m)	250	500	800	900
Advance time, t, (min)	130	279.74	459	548
Scaling factor (F)	1.418	1.447	1.415	1.492
	Scaled infiltration parameters			
a	0.077	0.077	0.077	0.077
k	0.06707	0.06846	0.06693	0.07058
f_o	1.98E-05	2.03E-05	1.98E-05	2.09E-05

Table D.11: Effect of advance distance on the predicted advance curves - Trial 1C

		Advance distance (m)			
		250	500	800	900
Distance (m)	Actual advance time (min)	Predicted advance times (min)			
0	0	0	0	0	0
250	130	134	136	134	140
500	279	287	291	286	299
800	459	480	489	479	502
900	548	565	606	562	

Table D.12: Effect of advance distance on the performance of the optimisation system - Trial 1C

Optimisation strategy				
DU $\geq$				
RE $\geq$	90			
AE $\geq$				
	Advance distance (m)			
	250	500	800	900
Predicted Performance (%)				
AE	72	71	73	69
AE (with 90% recycling)	72	71	73	69
DU	65	70	67	60
RE	91	93	92	90
Inflow volume (m^3)	98	102.3	99	102.26
Drainage (%)	28	29.2	27	31.2
Runoff (%)	0	0	0	0
Time to cut off (min)	424	440	424	440

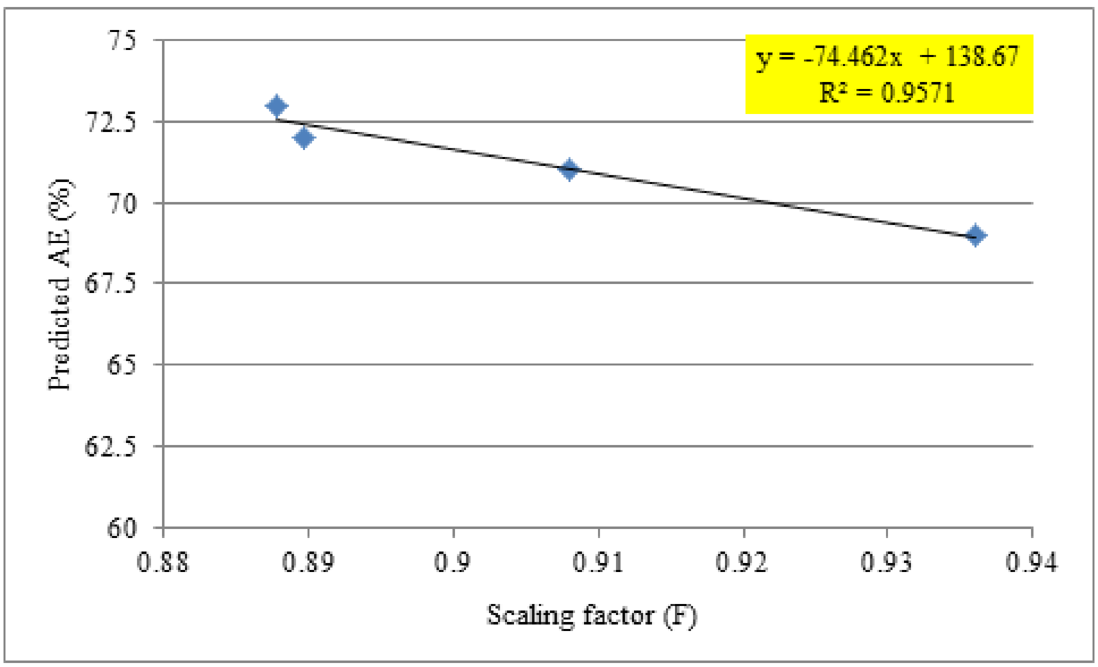


Figure D.1: Scaling factor (F) versus predicted AE (%) - Trial 1C

D.1.2 Trial 1D

Table D.13: Effect of advance distance on the scaling factor - Trial 1D

Trial 1D model curve values						
a	0.03050					
k	0.05261					
f_o	3.09E-04					
r	0.59225					
A_o (m^2)	0.02966					
σ_y	0.77					
σ_z	0.97798					
Q_o (l/s)	2.6					
	Scaling process					
Q_ot (m^3)	19.19	40.72	62.23	80.03	102.02	122.46
Advance distance, x, (m)	100	200	300	400	500	580
Advance time, t, (min)	123	261	398.94	513	654	785
Scaling factor (F)	2.026	1.620	1.327	1.096	0.956	0.8746
	Scaled infiltration parameters					
a	0.03050	0.03050	0.03050	0.03050	0.03050	0.03050
k	0.10658	0.08521	0.06980	0.05765	0.05029	0.04601
f_o	6.26E-04	5.00E-04	4.10E-04	3.38E-04	2.95E-04	0.00027

Table D.14: Effect of advance distance on the predicted advance curves - Trial 1D

		Advance distance (m)					
		100	200	300	400	500	580
Distance (m)	Actual advance time (min)	Predicted advance times (min)					
0	0	0	0	0	0	0	0
100	123	117	91	75	63	56	52
200	261	378	246	186	149	130	119
300	398		818	386	274	228	205
400	513				519	378	325
500	654					773	540
580	785						

D.1.3 Trial 2D

Table D.15: Effect of advance distance on the scaling factor - Trial 2D

Trial 2D model curve values					
a	0.01087				
k	0.17825				
f_o	2.63E-05				
r	0.95862				
A_o (m^2)	0.02809				
σ_y	0.77				
σ_z	0.98947				
Q_o (l/s)	2.4				
	Scaling process				
Q_ot (m^3)	18.86	41.47	64.16	84.24	108.00
Advance distance, x, (m)	100	200	300	400	500
Advance time, t, (min)	131	288	445.56	585	750
Scaling factor (F)	0.890	0.970	0.989	0.960	0.974
	Scaled infiltration parameters				
a	0.01087	0.01087	0.01087	0.01087	0.01087
k	0.15857	0.17292	0.17621	0.17107	0.17356
f_o	2.34E-05	2.56E-05	2.60E-05	2.53E-05	2.57E-05

Table D.16: Effect of advance distance on the predicted advance curves - Trial 2D

		Advance distance (m)				
		100	200	300	400	500
Distance (m)	Actual advance time (min)	Predicted advance times (min)				
0	0	0	0	0	0	0
100	131	132	143	145	141	143
200	288	271	293	298	290	294
300	441	413	447	455	443	449
400	585	558	604	615	598	606
500	750	706	764	778	757	767

Table D.17: Effect of advance distance on the performance of the optimisation system - Trial 2D

Optimisation strategy					
DU $\geq$					
RE $\geq$	90				
AE $\geq$					
	Advance distance (m)				
	100	200	300	400	500
Predicted Performance (%)					
AE	89	81	80	82	81
AE (with 90% recycling)	89	81	80	82	81
DU	68	68	68	65	66
RE	91	91	91	90	91
Inflow volume (m^3)	97	108	110	106	108
Drainage (%)	11	19	20	18	19
Runoff (%)	0	0	0	0	0
Time to cut off (min)	680	744	760	728	744

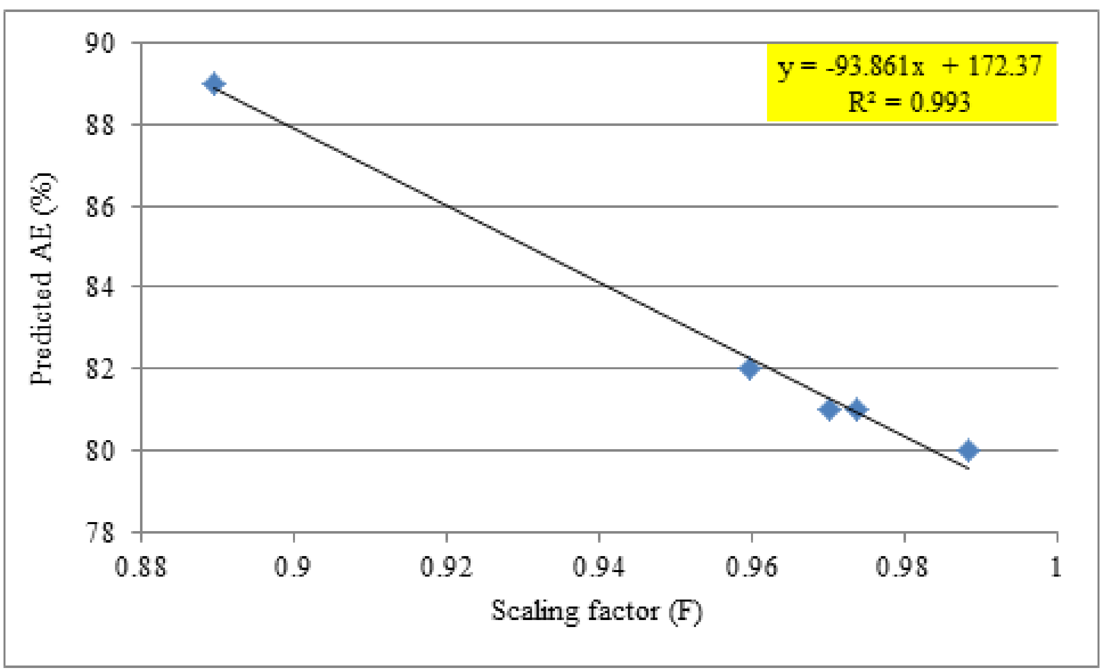


Figure D.2: Scaling factor (F) versus predicted AE (%) - Trial 2D

D.2 Effect of varying the flow rate - Trial 2D

The tables and figures illustrate the effect of varying the flow rate both in the case of the optimisation trials and the actual irrigations.

Table D.18: Effect of varying the flow rate (Q) on AE and RE

Change in Q (%)	Change in Q (l/s)	Optimisation system TCO = 760 min		Actual irrigation TCO = 760 min	
		AE (%)	RE (%)	AE (%)	RE (%)
100	4.8	44	100	44	100
75	4.2	50	100	50	100
50	3.6	59	100	58	100
30	3.12	68	100	68	100
20	2.88	73	100	73	100
10	2.64	79	100	80	100
0	2.4	80	91	83	94
-10	2.16	80	82	83	85
-20	1.92	80	73	83	76
-30	1.68	80	64	83	66
-50	1.2	80	46	83	48
-75	0.6	80	23	83	24

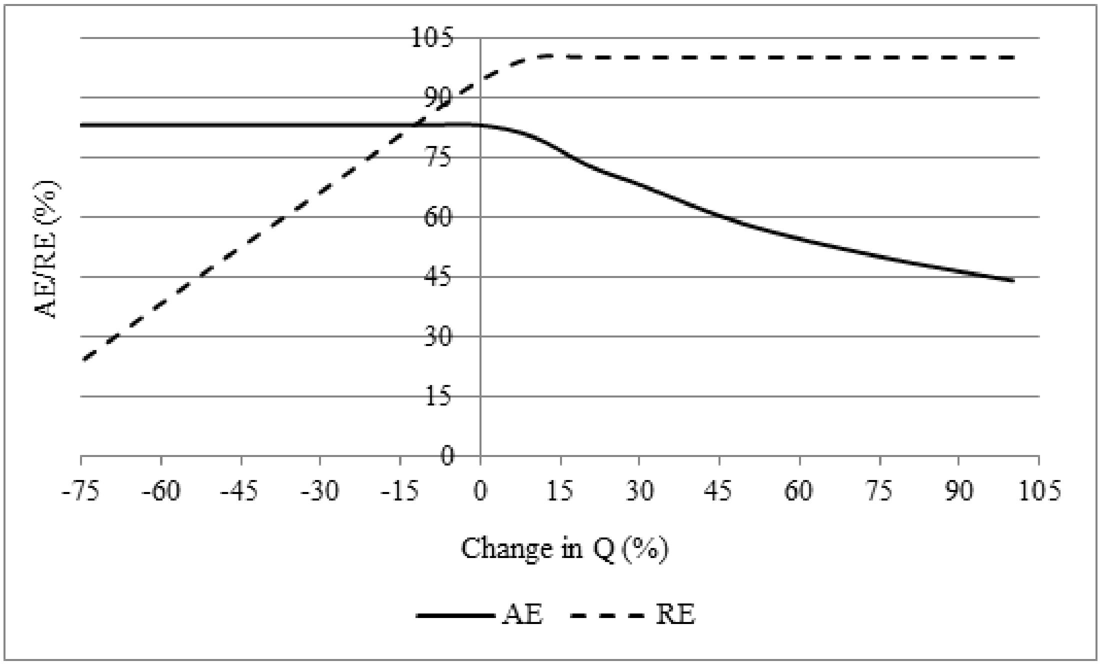


Figure D.3: Effect of varying Q on AE and RE (actual irrigation)

Table D.19: Effect of varying the flow rate (Q) on AE and TCO

Change in Q (%)	Change in Q (l/s)	Optimisation system AE (%)	Optimisation system TCO (min)	Actual irrigation AE (%)	Actual irrigation TCO (min)
100	4.8	82	376	85	360
75	4.2	82	424	84	408
50	3.6	81	504	84	488
30	3.12	81	584	83	552
20	2.88	80	632	83	632
10	2.64	80	680	83	664
0	2.4	80	760	83	728
-10	2.16	79	840	82	808
-20	1.92	79	952	82	920
-30	1.68	[1]	[1]	[1]	[1]
-50	1.2	[1]	[1]	[1]	[1]
-75	0.6	[1]	[1]	[1]	[1]

[1]RE below 90%

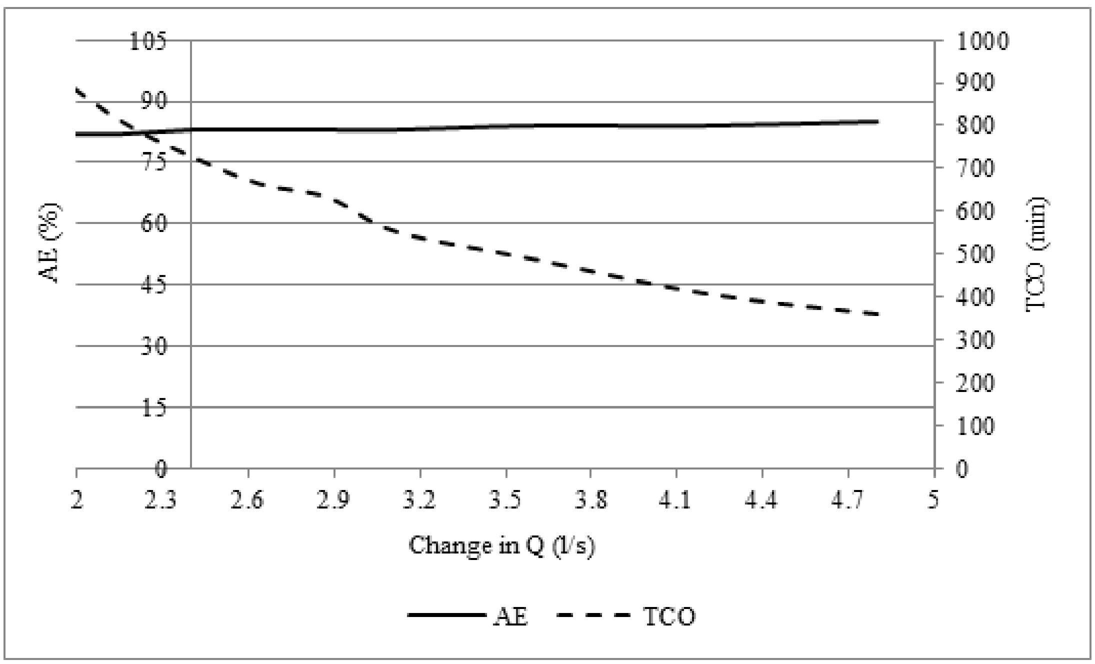


Figure D.4: Effect of varying AE and TCO (actual irrigation)