UNIVERSITY OF SOUTHERN QUEENSLAND

# TOWARD REAL-TIME CONTROL OF SURFACE IRRIGATION

A Dissertation Submitted by

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**To my wife and our daughters with Love**

Thank you very much.

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# ABSTRACT

The performance of surface irrigation is a function of the field design, infiltration characteristic of the soil, and the irrigation management practice. However, the complexity of the interactions makes it difficult for irrigators to identify optimal design or management practices. The infiltration characteristic of the soil is the most crucial of all the factors affecting the performance of surface irrigation and both spatial and temporal variations in the infiltration characteristic are a major physical constraint to achieving higher irrigation application efficiencies. Real-time optimisation and control has the potential to overcome these spatial and temporal variations and return highly significant improvements in performance. Calculation of the infiltration parameters from irrigation advance data is now the preferred method. If the process is to be included in a real time control system it must be done accurately, reliably and rapidly, and with a minimum of field data. Substantial work has been directed towards developing methods to estimate the infiltration characteristics of soil from irrigation advance data. However, none of the existing methods are entirely suitable for use in real time control. The greatest limitation is that they are data intensive and or unreliable and provide soil infiltration properties after an irrigation event.

A simple real-time control system for furrow irrigation is proposed that: predicts the infiltration characteristics of the soil in real-time using data measured during an irrigation event, simulates the irrigation, and determines the optimum time to cut-off for that irrigation. The basis of the system is a new method for the Real-time Estimation of the Infiltration Parameters (REIP) under furrow irrigation, developed during this research study, and that uses a model infiltration curve, and a scaling process to predict the infiltration characteristics for each furrow and each irrigation event. The underlying hypothesis for the method is that the shape of the infiltration characteristic for a particular field or soil is relatively constant (across the field and with time), despite variations in the magnitude of the infiltration rate or amount.

A typical furrow in the field is selected for evaluation (known as the model furrow) and its infiltration parameters ($a$, $k$, $f_o$) in the Kostiakov–Lewis equation are determined by a model such as INFILT or IPARM using inflow, advance and runoff

data. Subsequently the infiltration parameters for this model furrow can be scaled to give the cumulative infiltration curves for the whole field. In this process a scaling factor *(F)* is formulated from rearrangement of the volume balance equation and is calculated for each furrow/event using the model infiltration parameters and the single advance point. The performance of each furrow can then be simulated and optimised using an appropriate simulation model to determine the preferred time to cut-off

Using this new method, infiltration parameters were calculated for two different fields T & C. The SIRMOD simulation model was then used to simulate irrigation performance (application efficiency, requirement efficiency and uniformity) under different model strategies. These strategies were framed to assess the feasibility of and demonstrate the gains from the real-time control strategy. The infiltration evaluation results revealed that the infiltration curves produced by the proposed method were of similar shape and hence gave a distribution of cumulative depths of infiltration for the whole field that was statistically equivalent to that given using the complete set of advance data for each furrow. The advance trajectories produced by the proposed method also matched favourably to the measured advances.

The simulation results showed firstly that the scaled infiltration gave predictions of the irrigation performance similar to the actual performance. They also indicated that by adopting the simple real time control system, irrigation application efficiencies for the two fields could be improved from 76% for field T and 39% for field C (under usual farm management) to 83% and 70% for the fields T & C, respectively. Savings of 1239 $m^3$ in the total volume of water applied per irrigation over the area of 7.1 ha of both fields were indicated, which can be used beneficially to grow more crop. The proposed real-time control system is shown to be feasible. It requires few data for its operation and provides the infiltration characteristics for each furrow without significant loss of accuracy. The irrigation performance is improved greatly from that achieved under current farmer management and a substantial reduction in the volume of water applied per irrigation is achievable.

# CERTIFICATION OF DISSERTATION

I certify that the ideas, experimental work, results, analyses and conclusions reported in this dissertation are entirely my own effort, except where otherwise acknowledged. I also certify that the work is original and has not been previously submitted for any other award, except where otherwise acknowledged.

20/12/2007

Signature of Candidate — Date

(Engineer Kanya Lal)

**ENDORSEMENT**

Signature of Principal Supervisor — Date

(Professor Rod Smith)

Signature of Associate Supervisor — Date

(Professor Steven Raine)

# PREFACE

All of work reported herein is the original work of the author, contributing toward development of a practical real-time control system for furrow irrigation. Data on furrow irrigation advance for different soils analysed under this study were provided by the National Centre for Engineering in Agriculture (NCEA), USQ, Toowoomba.

Evaluation of methods for determining infiltration characteristics under different furrow characteristics and a range of flow rates and soil types is original and has been published as Khatri & Smith (2005). The new method developed for determining the soil infiltration characteristics from a single advance point in real-time, in conjunction with the new idea of model infiltration curve is novel. This has been published as Khatri & Smith (2006). Evaluation of the method, evaluation of different management strategies to assess the benefits from a simple real-time control and the conclusions reached are all original. This evaluation is being published as Khatri & Smith (2007).

Publications and national or international conference presentations arising from the work reported in the dissertation are listed below.

Khatri, K.L. and Smith, R.J., 2006. Real-time prediction of soil infiltration characteristics for management of furrow irrigation. Irrigation Science, 25(1):33-43

Khatri, K.L. and Smith, R.J., 2005. Evaluation of methods for determining infiltration parameters from irrigation advance data. Irrigation and Drainage, 54: 467-482.

Khatri, K.L. and Smith, R.J., 2007. Toward a simple real-time control system for efficient management of furrow irrigation. Irrigation and Drainage (In press)

Khatri, K.L. and Smith, R.J., 2005. Toward real-time control model for management of surface irrigation in Australia. Book of abstracts, International Conference on

Advances: In the Internet, Processing, Systems and Interdisciplinary Research. 10-13 November 2005 Venice, Italy. ISBN: 86-7466-117-3.

Khatri, K.L. and Smith, R.J., 2006. Simulation of the performance for a simple real-time control of furrow irrigation. Transaction of Wessex Institute of Technology, UK. International Conference on Sustainable Irrigation Management, Technologies and Policies. 5-7 September 2006, Bologna, Italy. Online ISSN: 1743-3541 / ISBN: 1-84564-043-8, Volume 6, p10-21.

Khatri, K.L., Smith, R.J. and Raine, S.R., 2006. Real time control of surface irrigation: managing infiltration variations and enhancing furrow irrigation performance. National Conference, IAA, Irrigation Association of Australia. 9-11 May, Brisbane. p73-74.

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Khatri, Kanya Lal
28th February 2007

# NOTATION

| | |
|---|---|
| $A_o$ | Cross sectional area of flow at the upstream end of the field ($m^2$) |
| $E_a$ | Application efficiency (percent) |
| $W_s$ | Volume of water stored in the root-zone ($m^3$) |
| $W_f$ | Volume of water delivered to the field ($m^3$) |
| $R_f$ | Volume of water lost as run-off ($m^3$) |
| $D_f$ | Volume of water lost as deep percolation below the root-zone ($m^3$) |
| $E_r, E_s$ | Requirement or storage efficiency (percent) |
| $W_r$ | Volume of water stored in the root-zone ($m^3$) |
| $W_d$ | Volume of water required in the root-zone |
| $DU, E_d$ | Distribution uniformity (percent) |
| $W_l$ | An average infiltrated depth of water in the lowest one quarter of the field (m) |
| $W_a$ | Average infiltrated depth of water over the whole field (m) |
| $Q, Q_o$ | Inflow to furrow or bay ($m^3$/min) |
| $t$ | Time of the advance phase of the irrigation (minute) |
| $A_x$ | Volume stored on the surface of the furrow or bay ($m^3$) |
| $Zreq$ | Desired depth of application prior to irrigation (mm) |
| $Z$ | Infiltrated depth (mm) |
| $a$, $k$, and $f_o$ | Modified Kostiakov infiltration parameters (constants) |
| $V_I$ | Volume infiltrated ($m^3$) |
| $V_S$ | Volume temporarily stored on the soil surface ($m^3$) |
| $V_R$ | Volume of run-off. ($m^3$) |
| $x$ | Advance distance (m) |
| $\overline{A}$ | Average cross sectional area of the surface flow |
| $\sigma_y$, | Surface storage shape factor ( Constant) |
| $\sigma_z$ | Sub-surface shape factor for the model infiltration function |
| $p$ and $r$ | Advance power function fitted parameters (constants) |
| $I$ | Cumulative infiltration ($m^3$/m) |
| $\tau$ | Infiltration opportunity time (min) |
| $Q_{out}$ | Irrigation runoff from end of field ($m^3$/minute) |

| | |
|---|---|
| $c$ | Constant of USDA infiltration model (0.007) |
| $F,\ \theta$ | Upadhyaya and Raghuwanshi fitted parameters |
| $x_{max}$ | Maximum possible advance distance (m) |
| $Z_{CR}$ | Depth of water infiltrated into soil cracks |
| $S,\ A$ | Philip and Farrell modified empirical parameters |
| $I_s$ | Scaled infiltration ($m^3/m$) |
| $t_{co}$ | cut-off time (min) |
| $t_{measured}$ | Measured advance time (minute) |
| $t_{simulated}$ | Simulated advance time (minute) |

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# Chapter 1

# Introduction

## 1.1. Background

Fresh water is a scarce resource in the world and irrigation is the major user of the fresh water supplies. Irrigation in the world today accounts for 70% of all freshwater withdrawals which are used to irrigate 17% of all cropped land; yielding 40% of the overall agricultural outputs worldwide (ICID Congress, 2005). Irrigation will play a greater and more dependable role in meeting future food demands than in the past. The goal shall be to ‘‘Grow More Food with Less Drops’’. This will be feasible with advances in technology, modernization, better management of irrigation and, where applicable, drainage systems. Poor irrigation management causes lower irrigation efficiencies and greater water losses. The United Nations predicts that if we continue to consume water at the current rate, two out of every three people on earth will have difficulty accessing fresh water by 2025. Individuals, organisations and governments must find better ways to make our limited water supplies go further (Natural Resources & Mines Qld, 2003). Therefore it is necessary to explore and develop management strategies, innovative technologies and practical models/tools that assist in raising irrigation performance and minimise the water losses for better irrigation, a better environment and a better future.

Surface irrigation systems are the most commonly used method for irrigating crops and pastures in Australia and around the world. Currently surface irrigation systems comprise more than 70% of the irrigated area in Australia, where as India, Pakistan, Brazil and many other developing countries are above 90% reliant on these systems. In this method water is applied directly to the soil surface from a channel located at up- slope end of the field and allowed to cover the field by overland flow. The rate of coverage is dependent almost entirely on the quantitative differences between inlet discharge and the accumulating infiltration. Secondary factors include field slope and surface roughness, such as soil clods or vegetation that retard water flow. There are two features that distinguish a surface irrigation from other systems: (1) The flow has a free surface responding to the gravitational gradient, and (2) the on-field means of conveyance and distribution is the field surface itself.

Using the soil surface to convey water across the field results in a low capital cost but it introduces unique problems in its design and management. Both design and management depend to a high degree on the soil properties such as infiltration rate and surface roughness. These properties can be difficult to measure or predict accurately, thus requiring a trial and error approach to develop proper design and management strategies (Hanson & Schwakl, 1994).

A surface irrigation event is composed of four phases named, advance phase, wetting or ponding phase, depletion phase (vertical recession) and recession phase (horizontal recession) as shown in the Figure 1.1.

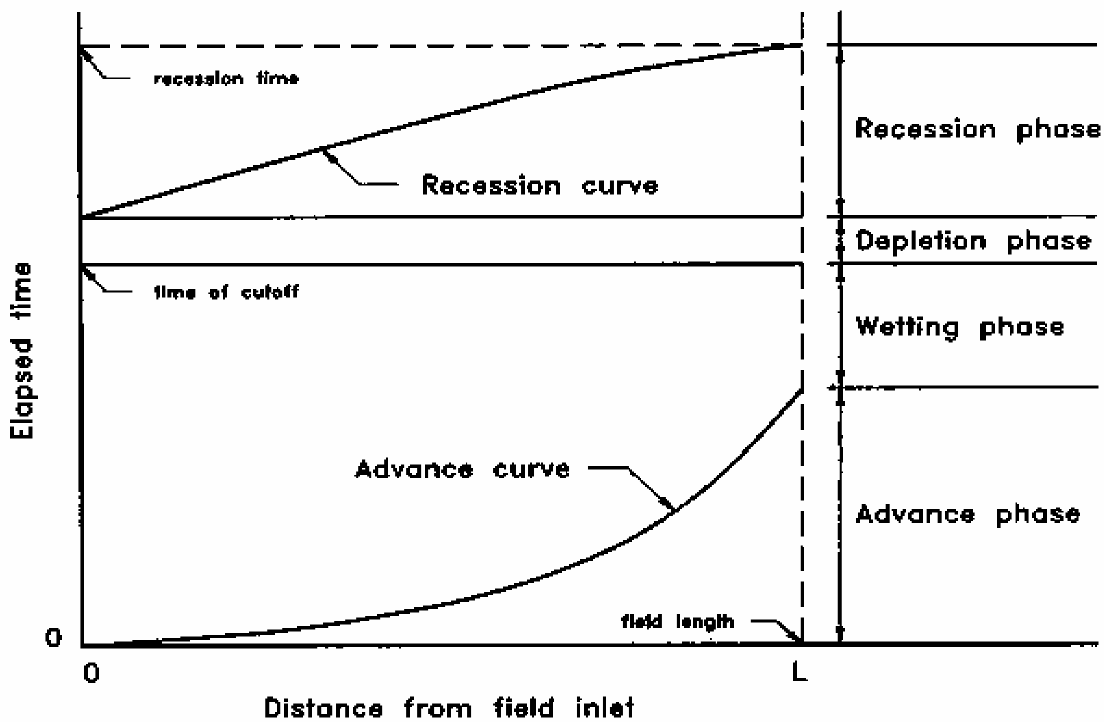



**Figure 1-1 Time-space trajectory of water during a surface irrigation showing its advance, wetting, depletion and recession phases (Walker, 1989; p7).**

When the water is applied to the field, it advances across the surface until the water extends over the entire area and it is called advance phase. Then irrigation water either runs off the field or begins to pond on its surface. The interval between the end of the advance and when the inflow is cut-off is called the wetting or ponding phase. The volume of water on the surface begins to decline after the water is no longer being applied. It either drains from the surface (runoff) or infiltrates into the soil. For the purpose of describing the hydraulics of the surface flows, the drainage period is subdivided into the depletion phase (vertical recession) and the recession phase (horizontal recession). Depletion is the interval between cut off and the appearance of the first bare soil under the water. Recession begins at that point and continues until the surface is drained.

In general, surface irrigation is perceived as an inexpensive, inefficient method of irrigating crops, bound by inherent characteristics and traditional practices to wasting much, if not most, of the water applied (Strelkoff & Clemens, 2003).

The efficiency of surface irrigation is a function of the field design, infiltration characteristic of the soil, and the irrigation management practice. However, the complexity of the interactions makes it difficult for irrigators to identify optimal design or management practices. While well designed and managed surface irrigation systems may have application efficiencies of up to 90% (Anthony, 1995), many commercial systems have been found to be operating with significantly lower and highly variable efficiencies. Previous research in the sugar industry (Raine & Bakker, 1996) found application efficiencies for individual irrigations ranging from 14 to 90% and with seasonal efficiencies commonly between 31 and 62%. More recently, Smith *et al.* (2005) reported application efficiencies in the cotton industry of similar range and magnitude.

The infiltration characteristic of the soil is one of the dominant factors in determining the performance of surface irrigation applications and both spatial and temporal variations in the infiltration characteristic are a major physical constraint to achieving higher irrigation application efficiencies (Shafique & Skogerboe, 1983). The spatial and temporal variation commonly found in infiltration characteristics (Raine *et al*., 1997) for a particular field also raises concerns regarding the adequacy of generalised design and management guidelines for surface irrigation.

A real-time control system has the potential to overcome these spatial and temporal variations. Raine *et al.* (1997) and Smith *et al*. (2005) have shown the potential significant improvements in irrigation performance are possible with optimization of individual irrigation events. Similar improvements in performance should be obtainable with real-time control.

## 1.2 Surface irrigation Techniques

Surface irrigation techniques can be broadly classified into uncontrolled flooding and the controlled methods of:

1. Border irrigation
2. Basin irrigation
3. Furrow irrigation

### 1.2.1 Border irrigation

This method makes use of parallel ridges to guide a sheet of flowing water as it moves down the slope. The land is divided into a number of long parallel uniformly graded strips 10 to 100 m wide and 200 to 1000 m long, known as borders that are separated by low earth banks/ridges. It has no cross slope but a uniform gentle slope in the direction of irrigation. The essential feature is to provide a surface such that water can flow down with a uniform depth. Each strip is irrigated independently by a sheet of water confined by the border ridges. The precision of field topography is of critical consideration but the extended lengths permit better levelling through the use of farm machinery. Border irrigation has the following characteristics.

- It is suitable for most soils where depth and topography permit the required land levelling at a reasonable cost and without permanent reduction in soil productivity.
- It is more suitable to soils having low to moderate infiltration rates such as loamy soils but unsuitable to coarse sandy soils having high infiltration rates.
- It is also not suited on soils having very low infiltration rates.
- It is suitable to irrigate all close growing crops like wheat, barley, fodder crops and legumes. It is mostly used in Australia for irrigating pastures.

### 1.2.2 Basin irrigation

Basin irrigation is a common form of surface irrigation, particularly in regions with layouts of small fields. This is the simplest in principle of methods of irrigation, is claimed to give higher application efficiencies and is being widely used in USA.

There are many variations in its use, but all involve dividing the field into smaller unit areas so that each has a nearly level surface. Bunds or ridges are constructed around the areas forming basins within which irrigation water can be controlled. The basins are filled to the desired depth and the water is retained until it infiltrates into the soil. When irrigating rice, or ponding water for leaching salts from the soil, the depth of water may be maintained for a considerable period of time by allowing water to continue to flow into the basins. This is similar to border irrigation except that here there is no longitudinal slope on the field and the length may be shorter.

Basins may vary in size from 1 $m^2$ used for growing vegetables to as much as several hectares for the production of rice and other grain crops (Larry, 1988). Sandy soils require small basins and clayey soils allow large basins. The objective in selecting the basin size is to enable flooding of the entire area in a reasonable length of time, so that the desired depth of water can be applied with a high degree of uniformity over the entire basin. Cotton, grain, maize, ground nuts, Lucerne (alfalfa), pasture and many other field crops are suited to this system of irrigation. It is seldom used for crops which are sensitive to wet soil conditions around the stems.

### 1.2.3 Furrow irrigation

Furrow irrigation avoids flooding the entire field surface by channelling the flow along the primary direction of the field using furrows, creases or corrugations. The size and slope of the furrow depends upon the crops grown, equipment used and spacing between crop rows. The furrows run down the slope of the land, between individual rows of plants, at spacings typically 0.75 to 1.5 m (Smith, 2005). Water infiltrates into the soil and spreads laterally to irrigate the areas between the furrows. The length of time required for the water to flow in the furrows depends on the amount of water required to replenish the root zone and the infiltration rate of the soil and the rate of lateral spread of water in the soil. Both large and small irrigation streams can be used by adjusting the number of furrows irrigated at any one time to suit the available flow.

The distinctive feature of furrow irrigation is that the flow into each furrow is set and controlled independently as opposed to borders and basins where the flow is set and controlled on a border by border or basin by basin basis. To supply water with borders one is also limited by the available capacity and volume in the supply channel. Of these methods, furrow irrigation is most commonly used in eastern and northern Queensland Australia (Figure 1.2).

**Figure 1-2 Siphons supplying furrow irrigated cotton Darling Downs, Queensland.**

Furrow irrigation can be used to irrigate all crops planted in rows; including orchards. It is suitable for irrigating maize, sugarcane, tobacco, cotton, groundnut, potato and other vegetables. It is suited to all soils except sandy due to high infiltration rates and has the following features.

- In this method water contacts only one half to one fifth of the land surface thus reducing crusting and evaporation losses.
- Furrows provide better on-farm water management flexibility under many surface irrigation conditions.
- Furrows provide the irrigators more opportunity to manage irrigations towards higher efficiencies as field conditions may change for each irrigation across field and throughout a season.

## 1.3 Overview of Research

### 1.3.1 Research hypothesis

The hypothesis to be addressed in this PhD study is that:

***The performance (efficiency, uniformity and adequacy) of surface irrigation can be maximized by the use of simple real- time control.***

The real-time control system envisaged would use minimum field data and would be able to predict performance and optimise and control the irrigation while the event is underway. The system would:

- monitor inflow and advance;
- calculate the soil infiltration characteristics;
- simulate the event underway and predict its performance;
- predict the optimum inflow and time to cut-off; and
- control the performance of the irrigation.

It is hypothesised that this approach can raise the efficiency of surface irrigation to a level comparable to that of other supposedly more efficient forms of irrigation.

### 1.3.2 Key issues identified for investigation

To deal with spatial and temporal variations of infiltration in real-time and thus improve the performance of surface irrigation, five key issues towards developing real-time control system have been identified and addressed in this dissertation. These are:

- Infiltration is a crucial factor affecting the performance of surface irrigation. Different infiltration estimation methods are available but their applicability to different soil types and situations is unknown. There are various tradeoffs and constraints that need to be considered when selecting a parameter estimation method. Methods differ in their data requirements, computational efforts, accuracy and robustness. Is there any robust method that can use minimum field data and provide the infiltration characteristics in real-time?

- A major obstacle in measuring the infiltration characteristic is the spatial and temporal variations in this parameter. A real time control system can over come these variations, particularly the temporal variations. Hence a model for prediction of infiltration in real-time is essentially needed to deal with these variations and achieve improved irrigation performance.

- The real-time model should require minimum field data (preferably only one advance point possibly measured at the mid way of the field while the advance is in progress) and should provide infiltration characteristics in real-time and without significant loss of accuracy. The advance produced by the real-time model should be equivalent to or match the advance measured in the field to justify the validity and accuracy of the new model.

- Model strategies should be framed to evaluate the quality and credibility of the infiltration characteristics given by the new model. This can be done by conducting irrigation simulations and to reproduce the irrigation performance equivalent to that given by actual infiltration characteristics. This should be tested for multiple irrigation events conducted under a range of furrow characteristics and inflow rates.

- Using the real-time model infiltration results, the different real-time control strategies should be tested to assess the benefits that could be achieved in irrigation performance by implementing a simple real-time control.

### 1.3.3 Specific objectives of research

To address the key issues described above leading to real-time control and management of surface irrigation for achieving improved performance, the following specific objectives have been designed for this research.

**1.** Evaluate current methods for predicting infiltration from irrigation advance data for various furrow characteristics, soil types, and advance and inflow rates.

**2.** Develop and test a method for predicting the infiltration characteristic suitable for use in real-time control, for various soil types and situations, and which requires an absolute minimum of field data.

**3.** Demonstrate by simulation the performance gains possible through various real-time control strategies, using existing irrigation data and models, and propose preferred models for practical real-time control.

➢ ***Evaluation of Current Infiltration Estimation Techniques***

The infiltration characteristic is a key determinant of irrigation performance and is routinely estimated from measurements of the irrigation advance using either the two-point method (Elliott & Walker, 1982) or the program INFILT (McClymont & Smith, 1996). Several other methods are available all of which:

- have different data requirements; and
- make different assumptions about the nature of the irrigation advance or about the nature of the infiltration characteristic and hence condition the problem differently.

The combined effects of these differences on the calculation of the infiltration characteristic are unknown as are the robustness of the various methods and their applicability to different soil types and situations. The most commonly used methods predicting the infiltration will be selected to evaluate their ability to predict the infiltration characteristics for different soil types and varying furrow characteristics. The tension between the accuracy and reliability of each method and the data requirement will be also assessed.

➢ ***Real-time Infiltration Model Development***

It is aimed to develop an infiltration model that will need minimum field data, one advance point possibly measured to the half way point of the field/furrow. The model would be capable to predict infiltration characteristics in real-time and without significant loss of accuracy. The testing of the model will be undertaken using existing irrigation advance data. The infiltration characteristics calculated by widely used INFILT program will be compared to those from the proposed method to demonstrate the accuracy and validity of the new method.

- ***Demonstrating Potential Gains from Real-Time Control***

The surface irrigation simulation model SIRMOD will be used to predict potential gains possible through various real-time control systems. Existing irrigation data for a variety of soils will be used to conduct these simulations. Irrigation performance under various real-time control strategies will be compared with the irrigation performance under usual farmer management and improved performance using recipe management strategies.

In particular, the effect on performance of varying the controlling variables after the irrigation has commenced will be assessed. In parallel with this assessment, a simple real-time control system will be proposed incorporating the infiltration model developed under objective 2. The system will be structured in such a way that it will be able to:

- calculate the infiltration characteristics in real-time;
- predict the performance; and
- control/optimize the irrigation while the event is underway.

## 1.4 Project outcomes/significance

For production areas on which surface irrigation remains the most sensible application strategy, there are a range of potential benefits to be gained from better in-field surface irrigation management including:

- increased application efficiency and increased water use efficiency (WUE), allowing more crop to be grown more profitably;
- decreased water loss below the root zone, hence reducing the risk of high water tables and salinity;
- minimised yield losses from waterlogging;
- improved capture of in-season rainfall; and
- enhanced sustainability.

This is an important and challenging project aimed at improving the performance of surface irrigation well above that which is possible with present management, modelling and control systems. It will combine field measurements of irrigation behaviour with advanced simulation modelling and analysis with the aim of:

> Raising surface irrigation efficiency from the existing 40 to 60 % up to 80 to 90% coupled with substantial savings in total volume of water applied per irrigation. Further more it will:

> Shift the focus of surface irrigation research from evaluation and remediation after the event to control and optimisation during the event (while the event is underway).

## 1.5 Structure of Dissertation

This dissertation contains 8 chapters addressing the importance and process of surface irrigation, performance measures of surface irrigation and key factors influencing the performance, the infiltration process, the most commonly used methods determining the soil infiltration characteristics, and development of a new real-time infiltration model. Furthermore to demonstrate the potential gains achievable in irrigation performance, different model strategies were framed and tested using field experimental data to conduct performance simulations and to evaluate a simple real-time control, which optimized irrigation performance by varying only the time to cut-off. The first four chapters provide the background to the research.

**Chapter 1** An overview of surface irrigation and its types and phases is presented in this chapter. Further the research hypothesis, key issues identified for investigation, specific objectives and outcomes / significance of this research study are defined.

**Chapter 2** This chapter is focused on unsteady flow equations, surface irrigation hydraulic variables and their impact on surface irrigation performance. Surface irrigation performance measures and the interactions between performance measures of surface irrigation are explained. The concept of surface irrigation modelling and optimisation is also discussed in this chapter. A brief review of the existing irrigation models is presented with the conclusion that a simple real-time control model would allow irrigation industry to efficiently manage the systems and achieve improved performance.

**Chapter** 3 The process of infiltration, infiltration equations and the impact of a number of factors influencing the soil infiltration phenomenon are explained in this chapter. A brief review on the infiltration equations and the methods for measuring infiltration characteristics from irrigation advance and field runoff is presented, concluding with the need for a new method that would require a minimum field data and provide soil infiltration information in real-time..

**Chapter 4** The problem of infiltration variability and its role in surface irrigation are elaborated in this chapter. The different sources of infiltration variability are explained and a brief review is given on the variability aspect of this parameter and its impact on the management of furrow / surface irrigated soils.

**Chapter 5** In this chapter the study related to the first major issue, that is, evaluation of the existing infiltration methods to test their suitability for the purpose of use in real-time control is presented. The most common methods using one advance point, two points and multiple points are briefly discussed. The results are presented of a comparison study performed to evaluate the ability of the competing methods to predict soil infiltration properties under different furrow characteristics and over a range of soils and situations. The tension between the accuracy and reliability of each method and the data requirement is also assessed.

**Chapter 6** In this chapter the focus is shifted to the second major issue identified for this research study, namely the development of a new real-time infiltration technique or model that should use absolutely minimum field data and be able to provide soil infiltration characteristics in real-time and without significant loss of accuracy. Further it deals with the third major issue which is the evaluation or testing of this newly developed model for real-time prediction of infiltration. The new approach is concluded to be suitable for use in real-time control.

**Chapter 7** The different model strategies are described in this chapter. These model simulation strategies were framed to address the fourth major issue related to evaluation of the ability of the scaled infiltration to reproduce irrigation performance equivalent to that given by actual infiltration characteristics. It is concluded that identical irrigation performance can be obtained under either strategy. Advance trajectories reproduced by the SIRMOD model using scaled infiltration were seen to be similar to the measured advance giving further evidence of the suitability of the scaled infiltration.

Under this chapter the fifth major issue is also addressed, related to demonstrating the potential benefits that can be achieved in irrigation performance using simple recipe management strategies, advanced real-time control and a simple real-time control strategy which optimised irrigation performance by varying only the time to cut-off. It shows the proposed simple real-time control to be feasible and under a simple real-time control strategy the irrigation performance could be improved greatly resulting in substantial reductions in the total volume of water applied per irrigation.

**Chapter 8** In this chapter the results of the previous chapters are put together, presenting a summary of the key findings and conclusions achieved under this study. Recommendations are also put forth for further research and development required in this ongoing research area.

# Chapter 2

# Surface Irrigation and Real-time Control

## 2.1 Introduction

This chapter is focussed on flow equations, surface irrigation hydraulic variables and their impact on irrigation performance and irrigation performance measures. A brief discussion on surface irrigation modelling and optimisation is also given here. The review of previous studies on the performance of existing irrigation models is presented with the conclusion that a simple real-time control model would enable the irrigation industry to efficiently manage the systems and achieve improved performance coupled with substantial savings in total volume of water applied per irrigation.

## 2.2 Unsteady Flow Equations

It is well known that surface water flow in irrigation can be described by the equations of Saint-Venant. Simulations of irrigation can be obtained by using the equations in their complete from or in certain instances one of three simplified forms, the latter offering economies of solution. The complete and three simplified forms of the equations are described below.

### 2.1.1 Complete hydrodynamic equations

The equations describing the flow of water over a soil surface express two physical principles, conservation of mass and Newton's second law, force equals mass times acceleration. These well know partial differential equations are known as the Saint-Venant equations. The mass-conservation equation is:

$$\frac{\partial Q}{\partial x}+\frac{\partial A}{\partial t}+I_x=0 \qquad (2.1)$$

and the equation of motion is:

$$\frac{1}{g}\frac{\partial V}{\partial t}+\frac{V}{g}\frac{\partial V}{\partial x}+\frac{\partial y}{\partial x}=S_o-S_f+\frac{I_xV}{gA} \qquad (2.2)$$

in equations (2.1) and (2.2) x is distance, (L); $Q$ is flow rate, ($L^3$ /T); $A$ is cross section area of flow, ($L^2$); $I_x$ is volume rate of infiltration per unit length of channel, (L/T); $g$ is the ratio of weight to mass, ($L/T^2$); $V = Q/A$ is average velocity in the flow cross-section, (L/T); $y$ is depth, (L); $S_0$ is channel bottom slope; and $S_f$, is channel friction slope.

Equation (2.1) is a mass conservation equation and implies the assumption that the water density is constant. It states that for a thin slice of space cutting across both the surface-water and infiltrated-water profiles (Fig.2.1), the time rate of increase in profile depths equals the negative of the gradient of discharge in the surface stream. It is evident that:

$$I_x=\frac{\partial Az}{\partial t}=B_z\frac{\partial z}{\partial t} \qquad (2.3)$$

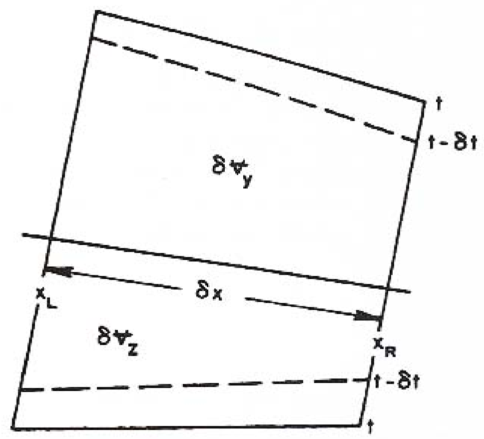



**Figure 2.1 Elementary slice through surface and subsurface profiles.**

In which $A$, is the volume of water infiltrated per unit length of channel. The second part of equation (2.1) is a definition equation for the depth of infiltration $z$, which depends upon the volume infiltrated and an arbitrarily designated infiltration width $B_z$ (Fig.2.1). In furrow irrigation, $B_z$ can be taken as the furrow spacing, and z would then represent the volume infiltrated, per unit plan area of field.

In equation (2.2), the depth gradient represents the unbalanced hydrostatic pressure force on the surface water contained in the slice of Fig. 2.1, the bottom slope is the component in the direction of flow of the gravitational force on the same element, and $S_f$, is the hydraulic drag (bed and vegetation) each expressed per unit length of channel, and each in ratio to stream weight per unit length of channel. The remaining terms then represent the inertial reactions to this unbalanced resultant force, also expressed per unit length of channel and in ratio to stream weight per unit length. The local acceleration $\partial V/\partial t$ is a direct measure of the unsteadiness of the flow. The convective acceleration $V\partial V/\partial x$, reflects the non-uniformity, and $I_x$ – $V/2gA$ represents a net acceleration stemming from removal of zero-velocity components of the surface stream at the bed by infiltration (Strelkoff, 1969).

The total drag on the flow in equation (2.2) must be determined empirically, customarily through experiments with uniform flow. Thus, the assumption is made that the unsteady, non-uniform flow in the irrigation stream experiences the same resistance as a steady uniform flow at the same depth and discharge. Errors from this source are also much smaller than those incurred in predicting resistance even in uniform flow. All of the uncertainty is lumped into the Chezy $C_h$, defined by the following expression for $S_f$,

$$S_f = \frac{V|V|}{C_h^2 R} \tag{2.4}$$

In which R is the hydraulic radius, (L). The Chezy $C_h$ is most commonly expressed through the Manning formula

$$C_h = \frac{C_u}{n} R^{1/6} \tag{2.5}$$

In which $n$ is the Manning coefficient, and $C_u$ is a unit coefficient ($C_u$ =1.0 in the SI system). Contrary to the concept of the Manning formula, in which $n$ is supposed to be a function of absolute roughness geometry alone, in the shallow, often vegetated channels used in surface irrigation, $n$ depends heavily on depth of flow.

Generally speaking, it can be added for practical purposes that the mathematical models of the surface-irrigation process, consisting of solutions of equation (2.1) and (2.2), are as precise as the input information provided to them. In practice, because inflow rate and bottom slope are relatively easily measures, the main source of input error lies with the roughness and in particularly with infiltration data.

### 2.1.2 Zero-inertia approximation

At the very low velocities normally encountered in surface irrigation streams, changes in velocity are negligibly small, compared to the force terms in the equation, and all inertial (acceleration) terms can be deleted. It was shown by a formal order-of-magnitude analysis (Katopodes and Strelkoff, 1977), that for normal Froude numbers below about 0.3, the forces acting on the surface stream are essentially in balance. The zero-inertia model thus comprises a numerical solution of equation (2.1) and equation (2.2) with all three acceleration terms deleted from equation (2.1), as follows:

$$\frac{\partial y}{\partial x} = S_o - S_f \tag{2.6}$$

The partial derivative notation is still used in equation (2.6), because depth is a function of both distance and time. At the same time it should be recognized that equation (2.6) is actually an ordinary differential equation representing conditions at one particular instant of time, and independent of time rates of change.

### 2.1.3 Kinematic wave approximation

If the bottom slope is sufficiently steep, the depth gradient of equation (2.6) is much smaller than either of the right-hand terms. The latter are then in essential balance. Thus;

$$S_f = S_o \tag{2.7}$$

everywhere, and the flow is at normal depth. Through equation (2.6), depth and discharge are simply related. as follows:

$$Q = AC_h \sqrt{R}\sqrt{S_o} \tag{2.8}$$

in which the first three terms are known as functions of depth. Any prescribed relation between depth and discharge coupled to a mass-conservation equation such as equation (2.1) yields a kinematic-wave flow model (Lighthill and Whitham, 1955). When the depth-discharge relation is one based on normal depth, the result is the so-called normal-depth model.

Since the Hydrodynamic model consists of both momentum and continuity equations, volume balance is essentially the continuity equation applied to the whole flow (rather than at a point in the flow) and that because continuity is the dominant of the two hydrodynamic equations then the volume balance equation gives a good description of the irrigation advance and of the controlling parameters. The volume balance model has been the basis of most design and field evaluation procedures (Walker & Skogerboe, 1987) and has been proven with field and laboratory data.

## 2.3 Surface Irrigation Hydraulics

***Variables***

Surface irrigation is an example of unsteady open channel flow with a lateral outflow (infiltration) where the governing equations are the Saint-Venant equations (continuity equation and momentum equation). These apply to both border and furrow irrigation, with the main difference being the shape of the flow channel.

While both the governing equations apply, it is the continuity equation that dominates. It is therefore possible to produce a quite acceptable model of the irrigation advance using only the continuity equation, or as it is more often called, the volume balance equation. The volume balance equation has been used here to gain an understanding of the surface irrigation process and to measure the relative importance of the different factors that influence the process.

At anytime $t$ during the advance phase of the irrigation, the volume applied to that time ($Q_o t$) can be equated to the volume stored on the surface of the furrow and plus the volume infiltrated to that time, i.e.

$$Q_o t = A_x + I_x \tag{2.9}$$

where the volume stored on the surface is represented by an average cross sectional area of the surface flow over the advance distance $x$, and the volume infiltrated by an average cumulative depth (or volume) infiltrated over that same distance.

Surface storage varies with time and is at a maximum for the first irrigation (Esfandiari & Maheswari, 1997). Some models assume a constant value for the surface shape coefficient. Models based on advance stage are more susceptible to errors in the surface storage (Renault & Wallender, 1997). Including the average cross-sectional area as an empirical parameter should be considered a technique to overcome variability in parameters such as slope, roughness and furrow geometry (McClymont & Smith, 1996). It then gives good estimation of surface storage equivalent to that is possible with measured $A_o$ and assumed $\partial_y$.

The factors or variables that control the performance of surface irrigation are:

- inflow rate and soil infiltration characteristic;
- surface roughness and longitudinal slope of the field;
- length of the field, time to cut-off; and
- desired depth of application

The impact that each of these variables has on the surface irrigation process can be determined through their presence in the volume balance equation, given above, or through their influence on the terms in that equation.

***Inflow Rate***

Inflow rate is explicit in the volume balance equation and is a most important variable in the surface irrigation process, second only to infiltration. Provided all other factors are held constant, the larger the inflow rate the more rapid the advance. However the rate of inflow has little impact on the rate of recession.

The rate of inflow may be constant throughout irrigation or may be varied at some time after commencement. For example, a large flow rate may be used during the advance phase and then reduce to a “cut-back” flow, more in line with the infiltration rate. This is maintained for the remainder of the irrigation to achieve the desired depth of application and desired uniformity of application. Irrigation performance is sensitive to the flow rate and care is required in its selection.

***Infiltration Characteristic***

The infiltration characteristic of the soil is explicit in the volume balance equation and is the dominant factor in determining the performance (efficiency and uniformity) of surface irrigation applications. Uncertainties in measurement of this parameter lead to poor irrigation system design and management (Strelkoff & Clemens, 2003). A high infiltration rate means a slow advance and rapid recession. Inability to account for spatial and temporal variability in this parameter is the cause of inaccurate predictions and low irrigation efficiencies.

***Surface Roughness***

The surface of the irrigation furrow provides a resistance to the flow. This resistance is a function of the roughness of the soil surface and the amount of vegetation that projects into or through the flow. It exerts its influence by affecting the area term in the volume balance equation (Smith, 2005). Surface roughness is manifest in the Manning $n$ coefficient in the Manning equation:

$$Q = (A/n)\, S^{1/2}\, R^{2/3} \tag{2.10}$$

The effect of this resistance on the advance and recession can be inferred from this equation. A rough surface means a high resistance and high Manning $n$. For a given discharge this results in a greater depth or area of flow and lower flow velocity. The advance is slowed, but not significantly, because of the greater volume of the water stored temporarily on the soil surface in the deeper flow. The recession is also slowed slightly. Selection of appropriate values for the Manning $n$ for larger scale flows is common practice and is based on a large body of experience. However for irrigation flows it is relatively easy to estimate $n$ from measurements of the discharge and cross-sectional area of the flow in an irrigation furrow or bay (Smith, 2005).

***Field Slope***

The longitudinal slope of the furrow influences both the advance and recession. Again this is evident through examination of the Manning equation. For a given discharge, increasing the slope increases the rates of advance and recession but only slightly. As with surface roughness, the influence of slope is a second order effect determined through its effect on the area term in the volume balance equation. For any irrigated field the slope is fixed at the design stage and can only be altered by a substantial land forming (earthworks) operation.

***Length of Field***

The length of field does influence the irrigation performance markedly. The longer the field the higher the flow rate needs to be to maintain a sufficiently fast advance rate. Inevitably the advance rate will slow toward the downstream end of the field making it harder to maintain equal opportunity times over the whole length of the field. The modern trend is for longer runs, often in excess of 1000 m, in contrast to the shorter lengths required for maximum efficiency of applications.

***Time to Cut-off***

Time to cut-off is a key management variable. Cutting the inflow off too soon will result in an insufficient depth of application, poor uniformity and the real possibility of the advance not reaching the bottom end of the field. If the cut-off is too late, the depth of application may be excessive with large losses of water in the form of deep percolation below the root zone and runoff from the end of the field. The application efficiency will be lowered.

***Depth of Application***

The desired depth of application is traditionally seen as fixed – determined from the irrigation schedule. However there can be some advantage in considering it as a management variable and under some circumstances it may be less than the Zreq (or deficit). *It* could be viewed as the maximum amount to be applied and that the actual amount applied in the irrigation may be reduced if it results in improved performance. The disadvantage is that the next irrigation would need to occur sooner to compensate for the reduced application. *It* does not affect the advance and recession curves.

Of the variables discussed above:

- Two are essentially beyond the control of the irrigator (infiltration and surface roughness);
- Two are fixed at the design stage (length and slope); and
- The remainder three (flow rate, time to cut-off and *Zreq*) are management variables able to be varied for and sometimes during individual irrigations.

The infiltration characteristic is the dominant factor of all the above variables affecting the performance of surface irrigation systems; and the variability of this parameter further complicates the situation for the growers to irrigate efficiently.

## 2.4 Performance measures of surface irrigation

The performance of surface irrigation mainly depends upon careful field design, infiltration characteristics of soil and the irrigation management practices. The objective of irrigation application is to apply the required amount of water as efficiently and as uniformly as possible. However different growers may place more or less importance on the three relevant performance measures namely surface irrigation application efficiency, requirement or storage efficiency and distribution uniformity. These can be described as fallows.

### 2.4.1 Application efficiency

This is defined as the ratio of volume of water stored in the root zone during irrigation to volume of water delivered in the field during that irrigation and usually expressed as a percentage (Michael, 1999). The components of the application efficiency terms are as indicated in the following equation:

$$E_a = \frac{100W_s}{W_f} \tag{2.11}$$

where $E_a$ is the application efficiency, percent;

$W_s$ is the volume of water stored in the root-zone and is given by:

$W_s = W_f - (R_f + D_f)$

$W_f$ is the volume of water delivered to the field

$R_f$ is the volume of water lost as run-off; and

$D_f$ is the volume of water lost as deep percolation below the root-zone

The scale at which application efficiency is determined depends on the spatial or temporal requirements of the project, and can relate to:

- Single furrow or whole field;
- Single irrigation or whole season.

In the words of Clemmens, application efficiency is the percentage of the applied water volume contributing to the plant requirement (Burt et al., 1997). When the minimum in the distribution just equals the target (required) depth ($D_{REQ}$), the efficiency is known as the potential application efficiency of the minimum ($PAE_{min}$):

$$PAE_{min} = \frac{D_{REQ}}{D_Q} \times 100\% \qquad (2.12)$$

with the volumes expressed in terms of field-wide equivalent depths ($D_Q$). When the requirement is just matched by the average of the low-quarter depths, the application efficiency is known as the low-quarter potential application efficiency.

### 2.4.2 Requirement efficiency

Requirement efficiency is a measure of the adequacy of an irrigation. It is defined as the ratio of water stored in the root zone during irrigation to water required in the root zone prior to irrigation (Michael, 1999). Storage or requirement efficiency terms are as indicated in the following equation:

$$E_s = \frac{100W_r}{W_d} \qquad (2.13)$$

where $E_s$ is the requirement or storage efficiency, percent;

$W_r$ is the volume of water stored in the root-zone; and

$W_d$ is the volume of water required in the root-zone prior to irrigation.

### 2.4.3 Distribution uniformity

Uniformity of irrigation systems is important to efficiency, yield and economics. The uniformity of water application is the key to high water application efficiency in any kind of irrigation system. Application uniformity concerns the distribution of water on the field which in surface irrigation systems is called distribution uniformity. It is defined as an average infiltrated depth of water in the lower one quarter (25%) of the field divided by the average infiltrated depth of water over the whole field. (Merriam & Keller, 1978). Other useful measures included standard deviation or coefficient of variation of water applied either into the total soil profile or at different depths of the soil profile during or after irrigation. The distribution uniformity can be estimated using the following equation.

$$E_d = \frac{100W_l}{W_a} \tag{1.3}$$

where $E_d$ is the distribution uniformity, percent;

$W_l$ is an average infiltrated depth of water in the lowest one quarter of the field; and

$W_a$ is the average infiltrated depth of water over the whole field.

### 2.4.4 Interaction between performance measures

Surface irrigation has an inherent disadvantage in uniformly distributing water over the field. This is because the same surface is used to absorb and transport water. The resulting variability in time of contact at points on the field from moving water over the surface results in non-uniform distribution.

Non-uniformity reduces application efficiency because in order to adequately irrigate the least watered area, the remaining areas are over-irrigated. The greater the difference in infiltration the greater the over irrigation and lower the efficiency.
Determining what constitutes the optimum irrigation is highly subjective and inevitably involves some compromise (Smith, 2005). The nature of the performance measures is such that it is impossible to maximize all three measures simultaneously. How the three measures interact is illustrated in Figure 1.3 below.

In this figure longitudinal infiltration profiles typical of surface irrigation are shown, each corresponding in turn to an increased time to cut-off and increased amount of water applied. In (a) section of figure, the flow is cut-off early. While the required depth of water is applied at the top end of the field, there is little or no infiltration at the downstream end and hence no run-off. Consequently the application efficiency is a high 100%. However the requirement efficiency $E_s$ and distribution uniformity $E_d$ are low.

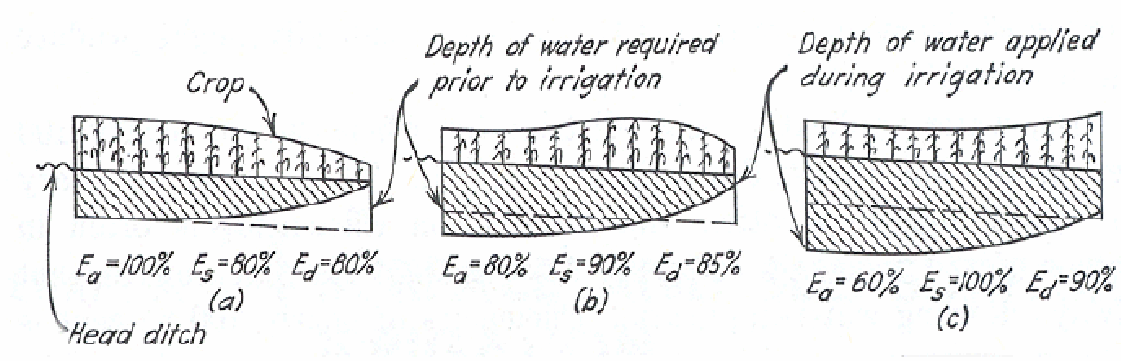



**Figure 2-2 Typical longitudinal infiltration profiles and the corresponding application and requirement efficiencies and distribution uniformities (Israelsen and Hansen, 1962).**

In (b) and (c) sections of the figure, the time to cut-off is increased in an attempt to better satisfy the crop requirements over the full length of field. The result we see here is that the requirement efficiency and uniformity increase to more acceptable values but the application efficiency falls dramatically due to over-irrigation over much of the field and to an increased volume of run-off.

To maximise or optimise the performance of surface irrigation, the key hydraulic variables such as field length, surface roughness, field slope, depth of application, infiltration characteristics, inflow rate and time to cut-off can be manipulated. The most important of these variables for the purpose of optimisation are: field length, inflow rate and time to cut-off. The optimisation benefits are ultimately dependant on careful prediction or measurement of soil infiltration characteristics.

## 2.5 Surface irrigation modelling

Surface irrigation systems have commonly been designed solely on the farmer's experience, traditions, and convenience, and not in accordance with engineering principles. Inadequate system design and management, coupled with inadequate irrigation scheduling practices, accounts for the poor performance of many surface irrigation systems. Over the last half-century, engineering concepts and various models have been developed to analyze and predict surface irrigation system performance and these models are able to assist farmers with design and management problems. While these models or tools have shown their value in the field, their use is not widespread, significant judgment and experience is required to produce reliable results, and in many cases they are not being used to their full potential. A key challenge to the application of these tools is the difficulty in characterizing system parameters, particularly those describing infiltration and hydraulic roughness (Strelkoff & Clemens, 2003).

Surface irrigation systems have the potential to be very efficient and return high crop yields. Simulation models enable optimization of the design and management of the systems and hence increases in the water use efficiency and uniformity of irrigation applications and reductions in the losses to deep drainage and tail water run-off. This can be through better design of field parameters such as slope and field length, or through better application design (management practices) involving inflow rate, cut-back rate, and /or time to cut-off. Benefits of increased efficiency include savings in total volume of water applied, increased yield, and hence profits to the farmer, and reduced environmental harm.

The mathematical modelling of water advancing down a furrow or bay is not new. Recent advancement in computer technology has led to the development of a large number of models of varying complexity. However none of these models currently fulfil the requirements for real-time control where the specific requirements are evaluation of the infiltration characteristic during the irrigation event and automatic real time simulation and optimization, although many do simulate the flow accurately and are suitable for the analysis of existing irrigation systems.

Surface irrigation models can be categorized into four main classes.

- Continuity or volume balance models
- Kinematic wave models
- Zero-inertia models
- Full hydrodynamic models

Each successive model in the above list contains extra terms adding to the complexity. Volume balance models utilize the laws of continuity with assumed shape factors to represent the surface and subsurface profiles. They are only suitable for a narrow range of conditions (Strelkoff & Kotopodes, 1977). Kinematic wave models assume that the friction or energy slope is equal to the bed slope. A uniform flow equation such as the Chezy, Manning, or Darcy Weisbach equation is included to relate the flow rate to water depth or cross-sectional area of flow. These models are not suitable for systems with zero or small slope or with restricted outlets.

The zero-inertia model includes a water depth gradient term, and includes pressure, friction and gravity components, but ignores inertial effects. This assumes negligible water accelerations.

The full hydrodynamic model includes a complete representation of momentum, and is very accurate but difficult to run. The extra complexity in the model may not be warranted. The addition of acceleration terms in the model can be unjustified as Froude numbers in most border systems are below 0.3 (Schmitz and Seus, 1992) implying that inertial forces are very small in comparison to gravitational forces. All models contain a degree of empiricism caused by assumptions in model design and simplifications in the numerical solution technique (McClymont, 1996). Models should contain a minimum of approximations so that they are not specific to a particular field situation.

## 2.6 Existing Models

Two models that seem to have gained the most recognition as complete models include the zero-inertia Strelkoff or SRFR model (USDA, 1997) and the hydrodynamic Walker or SIRMOD model (Walker, 2001). Both models are very similar in many ways but they handle some computational aspects differently.

SRFR provides more computational options and it solves the equations of mass and momentum conservation of general physics coupled to empirical formulas for time-dependent infiltration and the hydraulic drag of bed roughness and submerged plant parts upon the surface stream. The formulas are complemented with site-specific coefficients, input to SRFR as data, along with system geometry and inflow. The equations are solved in a series of time steps over the length of surface stream, found as part of solution (and leading to advance and recession as functions of time). Thus, at every computational time level, the flow depths and velocities are known at a sequence of points within surface stream. SRFR differs from the SIRMOD by allowing the Manning *n* to vary as a function of water depth. This ability lacks in SIRMOD and the Manning *n* is calibrated with the help of measured and simulated advance. A more general infiltration equation is also incorporated which resembles the Kostiakov-Lewis model with an extra term added.

SIRMOD employs user-selectable kinematic-wave, zero-inertia, and hydrodynamic simulations of overland flow in the surface irrigation environment. Infiltration, geometry, inflow flow hydrographs, and operational scheme are key model input parameters. Uniformity and efficiency are two key output parameters. Other inputs include field length, slope, width, and roughness; inflow rate and duration; infiltration parameters for the Kostiakov-Lewis equation; surge flow parameters if needed; description of downstream boundary conditions; cross-sectional shape; method of simulation. Evaluation is based on a two-point power law fit to advance data, and design is based on an optimised volume balance procedure. Simulation and evaluation are event-based and simulation sensitivity is primarily a function of how well the Kostiakov-Lewis infiltration parameters are defined.

Another model that shows promise is the Schemitz-Seus zero inertia model (Maheshwari & McMahon, 1993b). This model is unique in that an analytic solution has replaced the finite difference approximation to the derivative terms in the model. This is as far as the “analyticalness” of the model extends however, as it still requires an iterative solution technique at each stage in the simulation. It should present a substantial saving in computational power over other methods.

## 2.7 Previous studies on Model Performance

Maheshwari and McMahon (1993a) compared the performance of six surface irrigation models, including the Walker (SIRMOD) and Strelkoff models. Over sixty irrigations were monitored and the models applied. It was concluded that the Walker model was the best for predicting advance times and the Strelkoff best for the recession. More generally it was found that the models employing the hydrodynamic and zero-inertia approaches were the most appropriate. There was no difference in the results between the hydrodynamic and zero inertia approaches of the Walker model. This supports the assumption that other authors have made regarding negligible effects of inertia terms in border irrigation. Maheshwari and McMahon (1993a) found that the kinematic wave models had a tendency to under predict the recession, and also concluded that there was little advantage in using a discharge depth equation (Strelkoff model) over the Manning equation (Walker model) to represent hydraulic resistance.

McClymont *et al*. (1996a) performed a sensitivity analysis on the Walker model (SIRMOD) and found that the model was able to simulate the surface irrigation process adequately when sufficient data was available. However the model showed a tendency to under predict both the rate of advance and the volume infiltrated, which agrees with the findings of Maheshwari and McMahon (1993b). The model performed poorly when an accurate description of infiltration was not available.

The main objective of the model could be to optimize irrigation efficiency at the plot or field scale during the entire irrigation season through the analyses of irrigation practices. Owing to spatial and temporal variability of soil properties, this objective is not easy to achieve. Wetting and flooding can induce soil structural changes (Collis-Georges & Greene, 1979; Kemper & Rosenau, 1984; Or, 1996), and as a result, the infiltration properties may vary from one irrigation event to the next even in similar soil moisture conditions. Soil capillarity changes right from the first irrigation event to the next during the same season. At the same time soil compaction and cracking magnitude increase in heavy clay soils thus further complicating the situation for achieving optimum management. Mailhol *et al*., 1999, concluded that Optimization of efficiency could only be obtained by means of a modeling approach of the advance-infiltration process taking into account the spatial and temporal variability of the infiltration characteristics.

## 2.8 Real-time Control

Surface irrigation systems are most efficient where optimised under real-time control strategies. The term real-time control applied to the analysis of field parameters in surface irrigation/furrow irrigation means that irrigation information is collected, studied and processed during the irrigation. The results obtained are used to modify the management variables for the same irrigation. The necessary information can be obtained from advance data, recession data, or field run-off.

A study to identify the potential improvement in irrigation performance achievable through real-time control strategies was undertaken by Raine *et al.* (1997). The flow rate and application time required to maximise the application efficiency was calculated for each individual irrigation throughout the season. These management variables were then used in simulations of individual irrigations using SIRMOD. Irrigation performance was assessed in each case by the application efficiency, the storage efficiency and the distribution uniformity as shown in Table 2.1.

Table 2.1 shows that when the management parameters were optimised for each irrigation throughout the season to simulate Perfect Real-time Control of individual irrigations, the average application efficiency increased significantly from 41% to 93% with a storage efficiency of 90% and with no significant difference in the distribution uniformity.

**Table 2.1 Irrigation performance efficiencies under different management practices.**

| Management practice | Application efficiency % | Storage efficiency % | Distribution uniformity % |
|---|---|---|---|
| Usual farm practice | 41 | 98 | 92 |
| Using average infiltration | 71 | 83 | 93 |
| Real-time control | 93 | 90 | 88 |

(Adopted from Raine *et al.*, 1997)

Smith and Duke (1984) modified the two-point method proposed by Elliott and Walker (1982) to determine infiltration characteristics in real time from advance data. They developed a remote sensing system to automatically measure the advance time and they looked for the optimum placement for sensors using the kinematic wave model. The best location for a two sensor system was between 40 and 60% of field length.

Walker and Busman (1990) developed a computer model for simulation and optimization of surface irrigation in real-time, combining a kinematic wave model and a Simplex optimization technique that minimizes the sum of squares of differences between the measured and simulated advance by fitting the three parameters of the modified Kostiakov equation. Azevedo *et al.* (1992) developed another computer model called SIRTOM (Surface irrigation real-time optimisation model) to estimate the infiltration parameters from advance data in real-time. They used a combined procedure of optimisation. First they obtained initial values from the parameters using the two point method. Later they used a multidimensional optimisation technique, called the Powell method, considering the parameters obtained with the two point method as initial values. That technique combined with a kinematic wave model permits the best search direction to be found. Finally they used one-dimensional optimisation technique called the Brent method to obtain the parameters $k$ & $f_o$ of the Kostiakov-Lewis equation. The parameter $a$ is determined by the two point method.

This model also incorporates computational analyses to evaluate irrigation system performance and can handle two different inflow management options; constant inflow during the entire irrigation event, and an innovative variable inflow strategy that corresponds to a feed back control logic. The model predicts the irrigation event performance and lets the user go through the variable inflow options to investigate the effects of inflow adjustments on the hydraulic conditions of the actual irrigation event, allowing for possible improvements in system performance. It is being used in Brazil for monitoring seasonal irrigation performance. However the model is not in common use due to the model complexity (Schwankl *et al*. 2000).

Camacho *et al*. (1997) developed the IPE (Infiltration parameter estimation) model for management and control of furrow irrigation in real-time. This simulation model allowed estimating infiltration parameters in real-time. The model simulated irrigation using a kinematic-wave model. The objective was to find the infiltration parameters that simulate water advance best fitted to the field measured data. The down hill simplex method was used in the model for this purpose. The model estimated the parameters only (k) and (a) of the Kostiakov–Lewis equation, where the parameter (fo) was to be initially calculated by using indirect methods.

The potential limitation of the above models is that, they are data intensive and difficult to operate. The IPE model also requires the infiltration parameter (fo) to be measured separately.

Trout (1992) concluded that infiltration varies from furrow to furrow and indeed along each furrow, causing variations in net applications, runoff and efficiency. If the efficiency is to be improved without sacrificing application uniformity and crop yield, good real-time management should be achieved by controlling the furrow inflow rates according to respective infiltration rates at the soil surface / individual furrows / field under unrestricted water supply. This infiltration rate is function of time and depends also on site conditions such as roughness, surface sealing, furrow cross-section and wetted perimeter. Therefore it is important that infiltration equation should describe, as well as possible, the infiltration under the conditions that apply to the specific irrigation event. An infiltration equation determined by a technique that performs a volume balance of the advance phase, adequately represents the actual infiltration conditions (Serralherio, 1995). Besides real-time irrigation management it can be used for design of irrigation systems where similar infiltration conditions or management problems are expected.

## 2.9 Conclusion

The most important variable inputs in design and management of surface irrigation are the infiltration parameters. Temporal variations in the infiltration parameters are highly important. The infiltration conditions of soil tend to change between the irrigation applications due to factors such as differing initial moisture content and degree of compaction. This requires the infiltration parameters should be measured while the particular irrigation event is in progress. Therefore the available infiltration estimation methods should be tested to evaluate their ability to estimate infiltration characteristics.

Review of existing simulation models has shown that they could be slow, unreliable, sensitive to input data and quite difficult to operate. This have been attributed largely to the solution process involved, however, unnecessary complexity of the model can also have an adverse effect. The solution technique utilized in operating the model is the decisive factor toward the success of the model as a tool. This problem is important with the zero-inertia and full hydrodynamic models which contain differential equations which are usually solved by finite difference approximation or finite element methods. This is not the case with volume balance and kinematic wave models which are relatively easy to solve but do not apply to many types of field conditions. A loss of accuracy can also be incurred through simplifying the solution technique to increase reliability.

A draw back to most existing models is the extensive amount of data, comprised of detailed field geometry, measurement of advance at different locations along the length of field or furrow, description of infiltration, inflow and runoff hydrographs, and hence the extensive field measurements, needed to run the simulations. . In most cases the difficult one included a description of infiltration measured before the irrigation event has occurred. This can lead to problems arising from temporal variability of infiltration.

Another limitation of nearly all the current models is that they are essentially simulation tools and are unable to optimise irrigation performance. Design of better performance is achieved through a trial and error approach of repeatedly running the simulation, a major hindrance to real-time control. The “user plays” approach requires a degree of skill on behalf of the operator, and can lead to problems caused by entering unrealistic parameter values. For example, the Walker model has been found to be sensitive to the range of input parameter values and the program often crashed (McClymont *et al.,* 1996a) with the input of unrealistic data.

An area in which existing models perform poorly and one, indeed, in which relatively little work has been undertaken is that of optimisation and modelling of surface irrigation performance under real-time control. Therefore the opportunity exists for a fast reliable model that is simple to use, requires a minimum field data and is able to predict soil infiltration characteristics in real-time, and determine the optimum management variables, in particular, time to cut-off and or inflow to optimise and control the irrigation to achieve larger benefits in irrigation industry.

# Chapter 3

# Estimation of Infiltration

## 3.1 Introduction

This chapter is focused on the process of infiltration, infiltration equations and a number of factors influencing the soil infiltration phenomenon. A brief description of the infiltration measurement is presented and the different infiltration estimation techniques from advance data and field runoff are being reviewed.

## 3.2 Infiltration

The property of soils, of great importance to irrigators, is the time rate at which water will percolate into the soil, or the infiltration. Singer and Munns (1999) defined the infiltration as the path of liquid water into a soil. The rate of this process, relative to the rate of water application, determines how much water will enter the unsaturated soil zone, and how much, if any, will runoff (Hillel, 1980). Therefore this soil physical parameter is of paramount importance to the water economy of plant communities, surface runoff, deep percolation and plays a dominant role in the successful design and management of an irrigation system. The process is controlled by gravity and attraction of water to dry pores and surfaces (due to moisture tension). The depth of infiltration is determined by the initial soil moisture content, the properties of the soil and time that water is present on the surface.

The infiltration rate is much higher at the beginning of irrigation event than it is several hours later. Moisture tension may be zero in the surface millimetres of the soil, shortly after wetting, and may be very high a few millimetres below, thus causing a large downward force (in addition to gravity) pulling the water into the unsaturated soil. Several hours after wetting, these differences in tension may be very small, and gravity then becomes dominant force causing infiltration. The decrease of infiltration with time after wetting a soil is of importance in rainfall-runoff studies and irrigation management. A convenient means of expressing infiltration is in terms of millimetres lowering of water surface per hour. Infiltration is difficult to calculate accurately. This complex phenomenon of water infiltration into the soil plays a vital role in irrigation performance and exerts its influence by controlling the rate of advance of the irrigation water down the furrow or bay. Knowledge of spatial average value of this characteristic is required for design, evaluation and optimization of surface irrigation. Much is known about how water infiltrates the soil, yet we are unable to predict with reasonable certainty the rate that water will infiltrate the soil. This lack of predictive capability is largely a result of the magnitude of the temporal and spatial variability of infiltration and it has been considered as a major area of future research (USDA, 1998).

Infiltration in furrows can be significantly more complicated than in flat borders or basins due to the two-dimensional nature of the furrow cross-section. Infiltration in borders and basins is generally considered to be one dimensional (only downward). Infiltration in furrows can be influenced by the wetted width of the stream and lateral flow into the furrow bed. If gravitational forces dominate the infiltration process, e.g., in a very sandy soil, then infiltration may be directly proportional to the wetted width. If furrows are closely spaced and the soil is very heavy such that capillary forces dominate the infiltration, the lateral infiltration from adjacent furrows will meet and such that infiltration essentially occurs over the entire set width; i.e., for each furrow, infiltration becomes a function of the furrow spacing.

The main problem is that for many situations, infiltration conditions are in between these two extremes, and may differ significantly over time or along the length of run.

For example, infiltration at the head end of the field, where the flow rate and water depth are high, may result in infiltration after, say, 12 hours essentially governed by furrow spacing; while at the tail end where the flow rate and wetted width are significantly reduced and the infiltration opportunity time is short, infiltration may be strongly influenced by the wetted width.

The SCS design procedures for sloping furrows (USDA, 1984) use an infiltration function based on the wetted perimeter at normal depth, plus a constant of 213 mm to account for the lateral flow. This is reported as an average value from numerous tests. For irrigation of every furrow, this width should not exceed the furrow spacing. This width is then assumed constant over time and distance. The assumption with this procedure is that the SCS intake family for a given soil used for border-strip irrigation design can also be used for sloping-furrow design. In practice, this approach has not been very successful.

Infiltration really needs to be judged from field performance of the irrigation system. If a constant width is to be chosen for infiltration, it is simpler to express infiltration as a function of furrow spacing; recognizing that significant changes in wetted perimeter (e.g., from furrow shape or flow-rate changes) or furrow spacing (or whether all furrows are irrigated) may change infiltration constants based on furrow spacing. of wetted width on furrow infiltration. For mild slopes, high flow rates, closely spaced furrows and heavy soils; the infiltration can be assumed to be somewhat similar to that for borders (i.e., one-dimensional and based on furrow spacing), except there is a tendency for the infiltration rates to start higher and drop more quickly.

### 3.2.1 Factors influencing infiltration

A number of factors impact soil infiltration. Some of these are:

***Compaction***

Compaction reduces infiltration; the most important source of compaction is by machinery. A compacted zone (plow pan) or an impervious layer close to the surface restricts the entry of water into soil and tends to result in ponding on the surface. Ploughing agricultural lands produces soil compaction (Voorhes & Lindstorm, 1984, Blackwell *et al*., 1985) reducing soil porosity through the partial expulsion of permeating fluids, air and water. Because the density of the largest soil pores is reduced by the compaction mechanism, the infiltration rate is also diminished (Hillel, 1980). The infiltration rate is further reduced if the compaction occurs when the field is wet. Allen and Musick (1992 & 1997) studied the use of machinery to purposely reduce infiltration rates in a high infiltration rate soil. In one test the irrigation advance time was reduced by 47% after compaction. The first pass of the machinery had the greatest effect. The use of compaction in furrows could be applied in some situations to improve the uniformity of advance and simplify irrigation management.

***Aggregation, structure and soil texture***

Infiltration is largely influenced through soil aggregates, structure and texture (Singer & Munns, 1999). Soils that have stable strong aggregates as granular or blocky soil structure have a higher infiltration rate than soils that have weak, massive, or plate like structure. Soils that have a smaller structural size (having a less pore volume) have lower infiltration rates than soils that have a larger structural size.

The types of soil sandy, silty, clay can control the rate of infiltration. For example, a sandy surface soil has normally a higher infiltration rate than a clayey surface soil. Water standing on gravely or coarse sandy soils percolates into the soil so rapidly that the water surface may be lowered several millimetres in an hour. On fine textured clay soils, it may collect and stand on soil seemingly with very little infiltration for many days.

***Pores***

Pores are important considerations in studying water flow through unsaturated soil. They are channels for rapid movement of solutes and pollutants through soils. Volume of pores greatly influences the infiltration process. The bigger the volume of pores the higher will be the infiltration (Hillel, 1980). Continuous pores that are connected to the surface are excellent conduits for the entry of water into the soil. Discontinuous pores may retard the flow of water because of entrapment of air bubbles. Pores (macropores) have been defined by various authors (Allen & Musick, 1992) as having capillary potentials greater than -0.1 to -10.0 kPa or equivalent diameters of 730 to 10,000 microns. Organisms such as earthworms increase the amount of pores and also assist the process of aggregation that enhances the process of water infiltration.

***Crusting/ surface sealing***

Soil seals and crusts reduce soil infiltration rates and increase soil strength. A crust on the soil surface can seal the pores and restrict the entry of water into the soil. The infiltration rate through a surface seal is much lower than the rest of the soil mass. Surface sealing in a furrow occurs when the velocity of the advance causes erosion; the particles are deposited when the velocity decreases below a certain value. This shows that some parts of the field may have lower infiltration rates based on the velocity of the previous irrigation (Enciso- Medina *et al.,* 1998). The formation of surface seal is influenced by soil texture, aggregate stability, clay content and organic matter. The thickness of crust and type of crust is important (Fattah & Upadhayaya, 1996). Wet surface crusts have a lower initial infiltration than dry crusts because dry soils experience cracking which initially increases the infiltration.

***Soil moisture content***

The content or amount of water in the soil affects the infiltration rate of the soil. The infiltration rate is generally higher when the soil is initially dry and decreases as the soil becomes wet. Pores and cracks are open in dry soil and many of them are filled with water or swelled shut when the soil becomes wet. As they become wet the infiltration rate slows to the rate of permeability of the most restrictive layer.

***Organic Matter***

An increased amount of plant material, dead or alive, generally assists the process of infiltration. Organic matter increases the entry of water by protecting the soil aggregates from breaking down during the impact of rain drops. Particles broken from aggregates can clog pores and seal the surface causing decrease in infiltration. Other factors include water temperature and chemistry, positioning of stones in the soil and irrigation (Singh, 1997) with low quality water.

## 3.3 Infiltration equations

There are a number of infiltration equations available that attempt to explain the process of infiltration. The equations are empirical; they are based on experiments not theory. They require some technique to fit the infiltration function to the field data. Some examples of empirical infiltration functions are Horton equation, the Kostiakov equation and the Kostiakov-Lewis equation.

Studies have shown that for many types of field data, most empirical infiltration functions work equally well. Clemmens (1983) and Maheshwari *et al*. (1988) found, from infiltration tests conducted on various soils, that empirical formulas fit field data better than the physically based, Philip and Green-Ampt formulas; however differences among empirical formulations were not statistically significant. Similarly, Tarboton and Wallender (1989) compared formulations for furrow infiltration measured with blocked furrow sections and computed coefficients of determination greater than 0.99 for all equations tested. On the other hand, Clemmens (1981), Bali and Wallender (1987), and Childs *et al.* (1993) found that field data for field infiltration was best replicated with the modified Kostiakov equation. These results included borders and furrows, and they concluded most functions fit “well-behaved” data adequately, but problems are always encountered when fitting a function to data that is not “well-behaved” or have erratic measurements.

The Kostiakov and Philip infiltration equations are very interesting because of their simplicity. Philip (1957) indicated that the simplest infiltration equation (Kostiakov) predicts soil infiltration very well if infiltration times are short. The Kostiakov-Lewis equation was obtained by introducing a constant infiltration term in the Kostiakov expression in order to describe infiltration when times are longer. This equation is often used in surface irrigation design and evaluation and is most suitable of the available empirical functions.

The Parameters of empirical functions are interdependent, for example when fitting the Kostiakov parameters, the value of $k$ affects the value of $a$, depending on the field data, the calculated parameters can sometimes be negative and inconsistent with the physical process for times longer than the observed infiltration event. However in Kostiakov function or modified Kostiakov equation the value of $a$ should not be allowed to go negative. The main cause of this is an overestimation of $f_0$. In other words a negative value of $a$, indicates that $f_0$ is incorrect.

***Kostikov-Lewis Equation***

The Kostiakov-Lewis equation is also known as the modified Kostiakov equation (Walker & Skogerboe, 1987). The original Kostiakov equation assumes that the inflow rate diminishes to zero at large times. It is different from Kostiakov equation because it includes the steady infiltration rate ($f_0$). This final steady infiltration rate is necessary because field observations show that the infiltration rate does not approach to zero for a wide variety of soil types. The modified Kostiakov equation is of the form:

$$Z = kt^a + f_0 t \tag{3.1}$$

where $Z$ is the depth infiltrated (m),

$t$ is the time (minutes), and

$a, k, f_0$ are the infiltration parameters (constants).

The modified Kostiakov equation is preferred over other empirical equations because it is both flexible and can represent the steady final infiltration rate. The steady rate does not have a large impact during the first moments of the irrigation but plays an important role in later stages. The steady infiltration rate is usually reached well before the end of irrigation (Elliott & Walker, 1982).

The infiltration parameters represented by $a, k, f_o$ are constants and must be determined for each individual irrigation. One might expect that these values should remain stable over the field and remain unchanged for subsequent irrigations. This is often not the case; adjacent furrows with similar inflow rate may produce different parameters. The parameters also vary between irrigations (due to temporal and spatial variations). The first irrigation of the season usually produces unique infiltration parameters.

### 3.3.1 Infiltration measurement

The infiltration rate may be measured at a single point by a number of different instruments such as the by pass infiltrometer, single ring infiltrometer and double ring infiltrometer. These devices are effective measuring instruments but only take readings for a small area therefore don't take into account the variability of infiltration across the entire field (Norum & Gray, 1970). Rainfall simulators fail to give infiltration behaviour that occurs during a surface irrigation.

Ponding, where water is left to infiltrate over an area also has problems because it does not take into account the effect of moving water; this is also a limitation for the infiltrometers. The movement of water in the furrow will cause erosion and deposition that will impede the infiltration by surface sealing and particle settlement.

The most accurate and appropriate infiltration rates will be those achieved under field conditions. The data collected for the entire furrow length gives us an average value for the infiltration function.

Elliott and Walker (1982) evaluated various point infiltration methods and found that none of these techniques allow a simulation that predicts the advance or run-off observed in the field. Through their experience they have concluded that the most effective technique involves measuring the advance rates, hydraulic cross sections and tail water volumes. Ring infiltrometers and other instruments that use stagnant conditions tend to underestimate the cumulative infiltration while blocked or un-blocked furrow tests give a better approximation because they take into account the effect of flowing water (Baustista & Wallender 1985, Camecho *et al.,* 1997).

Many models that evaluate the infiltration parameters from field data still use an infiltrometer to measure the final infiltration rate ($f_o$). This simplifies the solution as now only two infiltration parameters *(a, k)* of the modified Kostiakov equation $I = k\tau^a + f_o\tau$ need to be estimated using the advance data, there are now only two unknowns in the infiltration equation rather than three.

The inflow-outflow infiltration measurement technique uses the difference between the tail water and inflow measurements to determine the infiltration. This technique is often used to calculate the steady infiltration rate ($f_o$). The difference between the two hydrographs when the run-off rate becomes steady is essentially the final infiltration rate. Trout and Mackey (1988) evaluated such techniques and determined that they were subject to large uncertainty that increases as the furrow length decreases. Despite this uncertainty, this technique is particularly useful when only two advance points are measured. The two point method is usually used to calculate *(a, k)* once the steady infiltration rate ($f_o$) is obtained.

## 3.4 Previous studies to determine infiltration parameters from advance data

Direct measurements of soil infiltration rates using a double ring infiltrometer or furrow infiltrometer cannot represent real infiltration rates along the entire furrow because of soil spatial variability. Thus infiltration measurements obtained from advance data are more representative of real infiltration (Camacho *et al*., 1997). There are a number of methods that have been devised for measurement of infiltration parameters, based on a volume balance approach. However the most of the methods are unreliable and/or expensive in terms of data requirements and the estimates can be further improved by inclusion of runoff data (Gillies & Smith 2005).

Infiltration is the most dominant factor affecting the performance of surface irrigation and remains a challenging input in evaluating and designing furrow as well as border and basin irrigation systems. Hence substantial accuracy is required for its measurement. Temporal variations in the infiltration parameters are also very important. The infiltration conditions of the soil tend to change between the irrigation applications due to factors such as differing initial moisture content and degree of compaction. Therefore the infiltration parameters measured while the particular irrigation event is in progress will result in a more realistic estimate of soil infiltration characteristics.

In comparison to direct infiltration measurement methods which are time consuming and require special equipment and skill to perform, volume balance methods are mostly preferred and they have been proved to be an attractive alternative to measure this important parameter from advance data (inverse problem). A number of methods have been developed for measuring the infiltration parameters from advance and or runoff data, the most common methods are summarized below.

| | | |
|---|---|---|
| 1. | Two-point method | Elliott & Walker (1982) |
| 2. | ALIVE | Renault & Wallender (1993) |
| 3. | Shepard one point method | Shepard *et al.* (1993) |
| 4. | Raghuwanshi method. | Upadhyaya & Raghuwanshi (1999) |
| 5. | Valiantzas one-point method | Valiantzas *et al.* (2001) |
| 6. | INFILT | McClymont & Smith (1996) |
| 7. | IPARM | Gillies & Smith (2005) |
| 8. | Linear infiltration | Austin & Prendergast (1997) |

Each of the above methods has specific advantages and opinions differ as to which is the best one. However, all are empirical and their usefulness depends on how they well represent actual infiltration and or the ease of use. A brief review of these methods and some more models developed to estimate infiltration parameters for efficient management of furrow irrigation is presented below.

Christiansen *et al*. (1966) developed a method to estimate infiltration parameters using an average infiltration rate based on advance times and distances but the method was data intensive. Elliott and Walker (1980) applied a volume balance method assuming an average area of the flow cross section and the method needed to measure ($f_o$) the basic infiltration rate. Reddell and Latortue (1986) developed a volume balance technique to evaluate mathematically the mean area of flow cross section from advance and recession data. Bautista and Wallender (1991) considered a least squares search technique to estimate the parameters from measured data on irrigation advance but they had great difficulty in determining the three parameters of the Kostiakov-Lewis expression.

Elliott and Walker (1982) developed the widely used Two-point method which incorporates the Kostiakov-Lewis equation in a volume balance model to predict the infiltration parameters $a$ and $k$ using advance data. The final infiltration rate must be measured separately. Input data includes the cross sectional area of the flow at the up stream end of the furrow or bay. Only two irrigation advance points are required. These are used to generate two non linear volume balance equations which are solved for the two unknown infiltration parameters. In the process of generating these equations a simple power equation is used to represent the advance. A logarithmic transformation is used to linearise the volume balance equations giving two linear algebraic equations with two unknowns. Therefore this approach could be thought of as the simplest of the nonlinear optimization procedures.

Although only two points are required the method still remains information expensive in that the basic infiltration rate and cross sectional area still need to be measured. Errors in the measurement of these quantities can lead to inaccuracies in the infiltration parameter values.

Renault and Wallender (1992) devised a model based on advanced linear velocity (ALIVE) to predict infiltration from advance rate along a field and to predict advance knowing the infiltration function. This method uses a flow rate theory rather than volume balance theory. The model assumes a Horton infiltration equation that circumvents the shortcomings of the Kostiakov equation for long times. The resulting exponential advance function describes advance more realistically than the power advance equation for short as well as long times.

Advance rate plotted against the distance along the field yields parameters to calculate the infiltration function and surface storage. More intensive measurements of advance, especially at the head end of the field, are needed to calculate the four parameters of the velocity diagram compared with other volume balance methods. Additional measurements of advance however provide estimate of storage that the other methods do not. Another benefit of the Alive theory is the ability to estimate the steady state infiltration rate without measuring the outflow; this is especially advantageous when the evaluation is limited to the advance phase. In addition to solving the inverse problem, the theory can be used to predict advance if the infiltration function, flow rate and surface storage are known. The method is less common due to the intensive data requirement and increased complexity.

Shepard *et al*. (1992) proposed a one-point method to predict infiltration parameters from advance time to the field end, flow rate and flow area using a volume balance principle. The volume balance equation originally suggested by Lewis and Milne (1938) was the starting point in the derivation of a model to estimate sorptivity $S$ and parameter $A$ in the Philip (1957) infiltration equation. By assigning the exponent in the advance equation ($r$) the value of 1/2, advance to the field end only completely defined the function, and here with advance time to any location was found. Field experiments to test the one point method were conducted in the San Joaquin Valley. For the one point method sorptivity $S$ was greater and parameter $A$ was lower than predicted from infiltrometer measurements and the Philip and Farrell method but the parameters compensated for one another and predicted infiltration agreed with the standard (neutron probe method).

This method can be used to predict average infiltration of an individual furrow using advance time to the field end, flow rate and flow area. But the method could not accurately estimate the distribution of water along the furrows with dramatic change in infiltration properties (shepard *et al*. 1992 ).

Upadhyaya and Raghuwanshi (1999) developed a semi-empirical equation for cumulative infiltration in a furrow irrigation system using an exponential wetting front advance equation and a volume balance technique. In this method infiltration is characterized by the exponential Horton equation. The advance is also described by an exponential equation, which avoids the short comings of the power law approach at short and long times (Renault & Wallender, 1992). They suggested that surface storage can be estimated in several ways. Lewis and Milne (1938) considered a constant stream cross section in time and distance, and Reddell (1981) assumed surface storage is negligible compared with infiltration and inflow. Burt *et al*. (1982) measured the cross section at different locations while the other investigators (Wilke & Smerdon, 1965, Singh & Chuhan 1972) multiplied a surface profile shape factor by the measured upstream flow cross sectional area or depth calculated using Manning equation.

Valiantzas *et al*. (2001) devised a one-point method to determine the infiltration parameters of the soil conservation service (SCS) equation. The time of advance at only one location of the field, inflow rate and average flow area are the field data required to estimate the two parameters of the SCS infiltration equation. The dependence of the two infiltration parameters, $k$ and $\alpha$, of the SCS intake function was expressed analytically and then the single unknown intake parameter of the SCS function, $\alpha$, could be determined by applying a volume balance equation using a power advance assumption. The method assumes that the advance follows a power function in general form, not restricted to exponent equal to ½ as in the Shepard method. A relationship between the two infiltration parameters $\alpha$ and k, allowed the infiltration estimate to be made with a single advance point and time. A simplified iteration procedure has been suggested to find the value of alpha. Seven independent sets of furrow evaluation data were used by the authors to demonstrate the validity of the proposed method using the one parameter SCS infiltration function. The method worked well for five data sets, two data sets were characterized by differences between the measured and predicted advance curves and did not give the satisfactory relationships. However authors claim that the method yielded more accurate estimates of the infiltration characteristics than Shepard's one-point method. The method showed poorer results when applied on Australian soils as discussed under Chapter 5 of this document.

Smith (1993) developed a method utilizing the same volume balance equations as the two point method of Elliott and Walker (1982); he found the parameters of

Kostiakov- Lewis expression by minimizing the volume balance error using a Steepest Descent procedure. His results, although initially appearing to be considerably different from the results of two point method, produced a cumulative infiltration curve that was almost identical. However unlike two point method, the steady state infiltration rate did not need to be measured separately as it was determined in the optimization. Data required were the cross sectional area of the water at the upstream end of furrow, inflow rate and three or more advance points.

McClymont and Smith (1996) refined the approach of Smith (1993) into the INFILT model to estimate infiltration parameters of the Kostiakov-Lewis equation from the measurements of furrow irrigation advance and inflow. To solve the equations for the infiltration parameters, an objective function was formulated based upon minimizing the sum of the squares of the error between the predicted and measured advance. The proposed method utilizes the full irrigation advance (at least two advance points) while data requirements are reduced substantially by omitting the need to measure the flow area and final infiltration rate. All three infiltration parameters and the average cross-sectional area of flow are determined from the optimization technique. To improve the reliability of the optimization and to make a program capable of implementation into a real-time control system, a simple but powerful line-search technique was developed and incorporated into the program.

The method differs from existing approaches in that only advance data and inflow rates are required as input data. The average cross sectional area of the flow ($\sigma_y A_o$) and the final infiltration rate ($f_o$) are treated as fitted parameters and need not be measured. By treating the average cross sectional area of flow ($\sigma_y A_o$) as an empirical parameter, the method accounts for variation in geometry (slope, cross section, roughness) along the length of furrow, better than is possible with the use of an assumed $\sigma_y$ with measured $A_o$.

The inclusion of final infiltration rate ($f_o$) as an empirical parameter is only likely to become a problem with high infiltration soils involving short advance times. Under these circumstances the fitted value may tend to zero and be much lower than the true physical value. This difficulty arises due to inability of the method to differentiate between the transient and steady state components of infiltration at the short advance times. This observation agrees with Bautista and Wallender (1993) who found that reliability of parameter estimates increased for relatively long advance times. The INFILT method is being considered to be very successful and accurate for the estimation of infiltration characteristics of a soil from irrigation advance data. The main features of the method follow.

a. The method has a built in optimization technique based on minimizing the difference between predicted and measured advance curves which requires no user intervention.
b. This method includes the final infiltration rate $fo$ and average cross sectional area of flow ($\sigma_y A_o$) as parameters evaluated in the optimization.
c. The method is able to handle noisy advance data effectively without the need to condition the data before use.
d. The method requires minimum of field data (in comparison to other existing methods) but requires accurate inflow data and provides quick results.

Gillies and Smith (2005) developed a model IPARM for estimation of infiltration parameters from advance and runoff data as an extension to INFILT method. The model uses a simplified optimization scheme that calculates infiltration parameters based on both the advance and storage phases of furrow irrigation. The technique gives improved estimates of the final infiltration rate over those techniques based on the advance only, without the requirement for the irrigation to last long enough to reach a steady run-off rate. The volume balance equation (law of conservation of mass) was used to describe the flow of water longitudinally down the furrow, including the infiltration of water into the soil. To represent the storage phase a run-off term is added to the volume balance equation of the two-point method:

$$Q_o t = V_I + V_s + V_R \tag{3.2}$$

where $Q_o$ is the steady inflow rate (m$^3$/min), $V_I$ is the volume infiltrated, $V_S$ is the volume temporarily stored on the soil surface, $t$ is the time (min) and $V_R$ is the volume of run-off.

This model performed satisfactorily for the 6 case studies as verified by authors. However like other techniques IPARM also suffers from a number of limitations, firstly the most crucial being the need for greater amounts of data. The model requires data collected almost over the entire irrigation period which could be a hindrance towards implementation of a real-time control. IPARM is based on, and draws from the optimisation techniques used in the INFILT software package, when using advance data only IPARM gives the same results as INFILT.

Austin *et al*. (1997) developed an analytical irrigation model that because of its simplicity represents a tool for improving water management in border irrigation. A simple linear infiltration function, ($Z = Z_{cr} + I_f\, t$) devised by Collis-George (1977), is shown to be appropriate for describing infiltration into duplex, red-brown earth. In this model cumulative infiltration, $Z$, is expressed in terms of the depth of water rapidly infiltrating into cracks and being sorbed through crack walls, $Z_{cr}$, plus the depth of water which infiltrates at rate $I_f$ over time $t$.

Many researchers have suggested the applicability of this equation for describing infiltration only into cracking soils (Evans *et al.,* 1990, Maheshwari & Jayawardane 1992, Mitchell *et al*., 1993).

This equation is suitable for describing infiltration into soils that exhibit shrinkage and cracking upon drying. It has two main advantages over the more usual infiltration functions. The first advantage is that the two parameters $I_f$ and $Z_{cr}$ have a physical interpretation. This allows their estimation in the field without the need to perform infiltration tests. The final infiltration rate ($I_f$) relates to the soil particle size distribution, with an inverse relationship between clay content and If. The extent of spatial and temporal variation in $I_f$ requires further field investigation; standard ring infiltrometers techniques have been suggested to be adequate to determine this variability. The crack fill component $Z_{cr}$, exhibits an inverse relationship with antecedent water content, which in turn exhibits a direct relationship with cumulative evaporation less rainfall ($E$ - $R$) since the previous irrigation. Further field investigation is also required to determine the exact form of the '($E$ - $R$) – $Z_{cr}$' relationships for various soil types.

Camacho *et al*. (1997) developed the IPE model, which simulated irrigation using a Kinematic- wave model. The objective was to find the infiltration parameters that best fitted the simulated water advance to the field measured data. The model estimated only the two parameters $k$ and $a$ of the Kostiakov–Lewis equation, where the third parameter $f_o$ was to be initially calculated by using indirect methods. Three methods were suggested to estimate ($f_o$). In the first method furrow was assumed as an infiltrometer and stabilized inflow and out flow rate was measured. In the second method the $f_o$ value could be obtained from published data in similar soils. The $f_o$ value could be considered constant during an irrigation season (Elliott *et al*., 1982). In third one, $f_o$ could be obtained from a field test using a double ring infiltrometer thus increasing the burden of field data collection.

## 3.5 Conclusion

The quest to extract the maximum information on soil infiltration from the minimum possible quantity of field advance data is of enormous importance, particularly for the automation of surface irrigation using real-time control.

The review of literature reflects the greatest limitation of existing methods is that they are data intensive. The hydrodynamic models require detailed furrow geometry and usually include the Manning *n* as one of the fitted parameters. Despite of excessive data requirements, the more complicated hydrodynamic models fail to take into consideration the spatial variability of measured quantities, which includes changes in the slope, the manning *n* and furrow geometry. Volume balance models have similar limitations. By including the average cross sectional area of flow ($\sigma_y A_o$) as one of the fitted parameters (as in INFILT method), it can be treated as an empirical rather than a physical parameter. Its resulting magnitude will then reflect the effect of spatial changes in the above mentioned variables.

The accuracy, speed and wide range of convergence of the INFILT method may make the model capable for use in real-time control and management of surface irrigation. But this method still suffers from limitations and requires four advance points in a field measured along the length of furrow (recorded by four sensors) to provide good estimation of the infiltration parameters; although other studies (Shepard *et al.*, 1993; Valiantzas *et al.*, 2001) suggest that it is possible to calculate the parameters by taking one advance point along the furrow. Hence there is a need to develop a technique or a model which may require only one advance point, possibly to the half way of the furrow, and provide infiltration parameters in real-time and without significant loss of accuracy.

# Chapter 4

# Infiltration Variability

## 4.1 Introduction

The purpose of this chapter is to consider the variability of infiltrated water, its causes and its effects. It is difficult to apply water uniformly with surface irrigation because soil conveys and infiltrates water over the field. A thorough understanding of field infiltration variability is essentially needed for efficient design, management and operation of surface irrigation systems. Evaluation of mean and variance of infiltration is challenging because soil properties vary in space and time and intake opportunity time also varies over the field creating a complex situation for irrigators to manage the systems efficiently. This chapter describes briefly the importance of infiltration variability in surface irrigation and the sources that cause infiltration variations. A brief review is presented on the variability aspect of the infiltration, finally concluding that real-time control and optimisation is the solution to overcome this extremely complicated phenomenon.

## 4.2 Role of infiltration variability

Surface irrigation is the most widely used irrigation method in the world but its irrigation efficiency is usually between 40 and 60% (Kruse & Heermann, 1977). Theoretically designed surface irrigation systems can achieve an application efficiency of up to 70-85% (Merriam & Keller, 1978). Low irrigation efficiency is usually due to high spatial and temporal variability of soil properties. As a result the soil infiltration characteristics are not accurately known and thus irrigation management is poor.

Several studies have reported large spatial variability in infiltration (Sisson and Wierenga 1981, Baustista and Wallender 1985, Tarboton and Wallender 1989, Childs *et al*., 1993). Baustista and Wallender (1985) reported 53 and 21% coefficient of variation (CV) for infiltrated volume and final infiltration rate respectively. Trout and Mackey (1988) reported 10-100% variation, with an average of 25% in the CV of final infiltration rate, based on measurement of complete furrows in 50 fields. These findings motivated studies on the effects of spatially variable infiltration characteristics on surface irrigation performance

A major obstacle to the measurement of infiltration variability is the spatial and temporal variability of infiltration properties. Field studies have shown that the coefficient of variation of infiltrated volume measured with infiltrometers on a single furrow can be greater than 50% (Bautista & Wallender, 1984). Volume-balance methods sample a larger surface than direct methods but furrow-to-furrow or border strip-to border strip variability within a field can still be large and comparable to the variability of actual water distribution (Tarboton & Wallender, 1989). In addition to the soil's textural components, soil management practices can alter infiltration variability (Hunsaker *et al.,* 1999). Studies have also analyzed the variability of infiltration over the irrigation season (Childs *et al.,* 1993) and the impact of variability on management decisions (Bautista & Wallender, 1993).

Despite the wealth of studies on infiltration variability, there is little practical guidance in the literature relative to sampling strategies. One generally accepted approach for dealing with variability is to use the infiltration adjustment procedures outlined in Merriam and Keller (1978). Their procedures, which apply to power law infiltration functions, are based on the premise that if the exponent $a$ can be estimated from infiltrometer-measured data, then the constant $k$ can be calculated independently from volume balance, based on the volume of water applied to a group of furrows or a border strip. Graphical or regression procedures used to fit infiltration data use the same data to calculate the parameters and, therefore, their values depend on each other. If infiltration is measured with indirect methods, a similar process can be applied if inflow and runoff measurements for an irrigation set are available. The approach can be applied as well to variations of the power infiltration law if values for other constants can be estimated. The adjustment procedures of Merriam and Keller (1978) assume that infiltration measurements used to determine $a$ are taken at more than one field location. They recommend using four samples in borders and basins and half-a-dozen furrows with furrow systems.

In furrow systems, soil variability and compaction by agricultural equipment causes differences in infiltration characteristics among furrows and, thus, the accepted practice is to measure infiltration on wheel and non-wheel furrows. Surge infiltration can decrease a soil's infiltration rate relative to continuous flow irrigation but the magnitude of the effect is soil dependent (Saleh & Hanks, 1989). Infiltration measurements for surge systems need to assess the magnitude of this effect.

Soil variability is not the only consideration when measuring infiltration characteristics. Soil management practices, surface effects, water temperature, and water quality are factors that affect infiltration and, thus, determination of intake parameters for irrigation system design or management still remains a challenging issue and needs to take into account possible changes in these factors under typical management conditions, to achieve efficient management of surface irrigation systems. A real-time infiltration prediction approach has the potential to account for these variabilities and highly efficient management of the systems is achievable with real-time control and optimization of individual irrigation events. Smith *et al.* 2005, conducted their study on irrigation application efficiency and deep drainage potential under surface irrigated cotton, analysing 69 data sets of irrigation events. They concluded that the full gains in irrigation efficiencies that can be achieved through an optimisation (that takes into account the temporal variability into soil infiltration characteristic) might only be attainable through the implementation of some form of real-time control.

## 4.3 Sources of infiltration variability

### 4.3.1 Inflow

The variations in roughness and slope can have an influence on the advance curve however the effect of variation in inflow may have an overriding effect. Initial inflow variation is still a problem with modern distribution systems (Renault & Wallender, 1996). Often it is impossible to determine from the advance curve if step inflow has occurred. Some times it can be noticed as a low $a$ but higher $k$. Variation in the inflow had the most significant effect on the CV, range of advance, CU and DU. Geometry remained the third significant factor and the roughness had the least impact, the field under study didn't have great variations (Schwankl, 2000).

### 4.3.2 Opportunity time

Opportunity time is considered more often as the cause of variable water depths in the field. Tarboton and Wallender (1989) discovered that the opportunity time may be equally responsible for the field variability but is often less important than variability in the infiltration characteristics. Intake opportunity time plays an important role in infiltration variability, especially for short intake opportunity times before the steady infiltration rate is achieved (Bautista & Wallender, 1985).

### 4.3.3 Wetted perimeter

Infiltration variability is related to wetted perimeter. Coefficients from models that neglect wetted perimeter are only valid if the inflow rate remains constant. Some models account for the wetted perimeter but don't allow it to vary with water depth. Camecho *et al.*, (1997) calculated the infiltration parameters with provision for a variable wetted perimeter with their IPE model.

Izadi *et al.,* (1985) found that the wetted perimeter is responsible for 25% of the variability in infiltration. The variation in wetted perimeter is more important early in the irrigation, while variability of infiltration plays a vital role later in the irrigation event. The occurrence of cracks and holes may over ride any effects that the wetted perimeter has on infiltration. Wetted perimeter is an important factor in the simulation of surface irrigation. Models that use a constant wetted perimeter result in over prediction of water advance and uniformity compared to a variable wetted perimeter model (Schwankle & Wallender, 1988). They concluded that the final distribution of water is strongly influenced by the wetted perimeter. Fangmeier and Ramsey (1978) found that infiltration is linearly dependent on the wetted perimeter.

### 4.3.4 Slope

The spatial distribution of slope has not been considered in the study of variability. Measurements of variable field slope are difficult to conduct and therefore are not likely to be considered in a practical situation (Zaptan & Playan, 2000).

Cavero *et al.,* (2001) found that variation in slope may have a large effect on the crop yield in a level basin. They discovered that 50% of the variability in crop yield could be represented in an irrigation model that accounts for a variable slope. The DU of irrigation reduced dramatically from 98% to 74%, if slope variability was considered.

### 4.3.5 Seasonal variability

Seasonal variability is caused by climatic conditions and cultivation practices (Elliott *et al*., 1983). Little can be done to eliminate these problems but irrigation design must be flexible so that the optimal management can be applied if the soil properties change throughout the season. It may be possible to make recommendations based on the first irrigation if the full nature of seasonal variability is known.

For the irrigated soils both the mean and variability of infiltration decrease greatly after the first irrigation (Childs *et al.,* 1993). The variation in infiltration is generally reflected in the parameter *k, a* is not affected to any extent, $f_o$ is also affected, it reduces by up to half of its initial value (Shafique & Skogerboe, 1983).

## 4.4 Previous studies on infiltration variability

The performance of the surface irrigation systems is highly affected by infiltration characteristic of soil. Spatial and temporal variations in the infiltration behaviour of surface irrigated soils are the major physical constraints to achieving higher irrigation application efficiencies (Shafique & Skogerboe, 1983).

Furrow irrigation performance depends on several field and management variables, which can be grouped into two categories namely, deterministic and stochastic. The largely deterministic factors such as furrow length, slope, spacing and irrigation application time can be quantified more accurately then the predominantly stochastic factors such as furrow inflow rate, infiltration characteristics, furrow geometry and roughness. Furthermore furrow inflow can be determined for a given furrow, but it may vary from furrow to furrow in an irrigation set. To evaluate the furrow irrigation performance more accurately as affected by infiltration variability and devise a sampling strategy, it is essential to study the impacts of these variables on furrow irrigation performance and rank them accordingly (Schwankle, 2000). Field data collection cost can be reduced if the efforts are focused on ensuring a high level of accuracy in the measurement of those variables to which the performance measures are most sensitive. Less influential variables having little or no impact can be measured with less accuracy or assigned typical value.

Under field conditions water is generally supplied to individual furrows via siphon tubes or gated pipe, with the intent being to set inflow rates uniformly on a set of equal length furrows. In some cases irrigators adjust the flow rate to obtain uniform advance rates among furrows rather than the same flow rate in every furrow. Even in such cases it may not always be possible to adjust the flow rate accurately in each furrow to obtain uniform advance among the furrows. Trout and Mackey (1988) measured the inflow rate variability of 15% in siphon tube, 25% for gated pipe and 29% for feed ditch water application techniques. This furrow to furrow inflow variability combines with furrow to furrow infiltration variability to produce even greater variability in furrow stream advance rate.

Furrow irrigators are aware of this stream advance variability (Trout, 1990). Their response is to increase inflow rates to ensure that adequate advance rates are achieved in a large portion of the furrows. This results in an increase in run-off rates. Although farmers may not be directly aware of the effect of infiltration variability on water application, they are aware that the crops in certain locations on their fields show signs of water stress earlier than other locations. Their response is to over-irrigate by extending the application time to limit the stressed area to an acceptable portion of the field. Extending the application time increases both run-off and deep drainage.

Trout, 1990, further concluded that the consequences of furrow-to-furrow inflow and infiltration variabilities are tail water run-off and deep percolation losses while a portion of field receives inadequate water. These variabilities cause an irrigator to increase inflow rates to achieve a desired advance time on the desired portion of furrows. Infiltration variability also causes an irrigator to irrigate longer to achieve adequate net application depths on furrows with low infiltration rates. Furrow to furrow infiltration variability will generally cause more water application variability than intake opportunity time (IOT) differences along furrows. A furrow irrigator generally must over-irrigate at least by 30% if he wishes to apply adequate water to over 80% of the field due to these variabilities.

Even by irrigation scheduling or soil moisture monitoring to indicate the correct average requirement and cut back inflows to match decreasing infiltration rates the furrow irrigator still must over-irrigate to attain high crop yields. He is faced with the practical management decision of choosing between an acceptable amount of water loss (including nitrogen loss which accompanies deep percolation) and the portion of the field he is willing to leave under-irrigated. The consequences can be statistically quantified if the infiltration variability is known. Only by overcoming or reducing these variabilities and reusing tail water run-off, he can irrigate efficiently without sacrificing yield. Much work has been done in this regard to improve the accuracy of irrigation models and to get improved performance of irrigation system through the improved application of irrigation management strategies but in reality any gain is overridden by the uncertainties relating to the variable nature of soil infiltration properties (Dagan & Bresler, 1993).

Tarboton and Wallender (1989) conducted their study on field wide furrow infiltration variability and found that control of the furrow irrigation system is influenced by field wide infiltration variability. The use of limited number of field measurements to obtain field wide infiltration variability was investigated using an adapted Philip equation because of its ability to use measurements from both neutron probes and blocked furrows and its ability to predict infiltration depth and separate infiltration variability into its components using variance analysis. Errors in estimating variability decreased as the number of furrows tested increased. However with as few as 3 furrows the coefficient of variation (CV) was only 6.8%. Childs *et al.* (1993) focused their study on the correlation of infiltration between different irrigations, using the measurements from irrigation 1 to optimize irrigation 2, the data from 2 to optimize irrigation 3 and so on. They noticed that the correlation between 2 and 3 is better than that between 1 and 2, the correlation between 3 and 4 even greater. They concluded that measurement of representative sites is more valuable than whole field evaluation. Temporal variability is more important than spatial variability within sites (Van Es *et al.*, 1999).

Infiltration variability in drip or sprinkler irrigation is easy to quantify because it is assumed to be dependent on the application system. Surface irrigation on the other hand is more complex because the depth of infiltration is dependant on the interaction between variability of infiltration rates and variability of opportunity times. Jaynes and Clemmens (1986) estimated spatial variability of infiltration in border irrigation from variability in infiltration function parameters and suggested that performance of the system was adversely affected due to this variability. Using the combination of variance techniques, Clemmens (1988) described sources of non uniformities in furrow irrigation. Results from this method agreed with simulated irrigation uniformity but were not compared to field measurements. The major source of irrigation non-uniformity was infiltration variability which was not subdivided into components. According to Izadi and Wallender (1985) wetted perimeter variability contributed one third of infiltration variability, while measurement error and soil variability contributed the remaining two thirds, but they did not quantify the influence of variable intake opportunity time.

Raine *et al.* (1997) conducted their study in areas with variable infiltration and monitored 17 irrigations on a single cane farm in Burdekin Delta. They concluded that significant ($P<0.05$) spatial and temporal variability in the infiltration function was observed through out the season. The substantial spatial and temporal variability observed with in the field soils also raises concerns regarding the errors associated with the recommendation of generalized design and management guide lines. A further difficulty in providing design and management guide lines under variable infiltration arises due to the interaction of the various irrigation parameters. More than seven variables affect irrigation performance and the interaction of these variables is multidimensional, hence, irrigation guidelines also need to be multidimensional.

Raine *et al.* (1997) collected data on the seasonal and spatial variability of the infiltration functions as seen within cane fields and investigated the effect of this variability on the identification of optimal irrigation management and design practices using the simulation model SIRMOD. However its use in selecting optimal values of the parameters is limited by the need to apply a trial and error approach (Raine and Bakker, 1996). Where the performance of SIRMOD was assessed for furrow irrigation of cane, it was found to consistently under predict (McClymont *et al.*, 1996) the measured advance times by an average of 22% and the measured infiltrated volumes by an average of 16.9%. This under- prediction was attributed to either uncertainties in the infiltration parameters (Maheswari & McMahan, 1993b) or a systematic error within the model (McClymont *et al.,* 1996).

The maximum efficiencies calculated for the season's lowest, average and highest infiltration functions, a range of water application rates and irrigation periods were used by Raine *et al.* (1997) to prepare charts showing the effect of variations in infiltration on the interaction of water application rate, period of irrigation and field length. For the site, maximum application efficiencies ranged from 48 to 70% for the highest infiltration function with storage efficiencies of almost 100%. How ever maximum application efficiencies for the lowest infiltration function were almost 100% with storage efficiencies of between 47 to 60 %.

Oyonarte *et al.* (2002) conducted a study on infiltration variability in furrow irrigation where the contribution of different sources of variability to irrigation water depth variability was quantified using a combination of variance techniques. This method was applied using field measurements from irrigation events performed on a loamy soil with low infiltration rate. Infiltration variability was estimated with blocked furrow infiltrometers. The assumptions made for the application proved to be valid as the major variability source turned out to be the soil intake characteristics, whose variance accounted for 45-71% of the variance in infiltrated depth under first irrigation conditions. Opportunity time and wetted perimeter were less variable in subsequent irrigations and the soil intake characteristics variability accounted for a percentage of total variance beyond 76%, being at times beyond 95%, so indicating the influence of soil intake characteristics variability that has proved to be particularly dominant, even when the experimental soil was apparently very homogeneous.

Spatial variability of the infiltration is often governed by a process whose origin can be attributed to cracking development, running furrow conditions or erosion, and inlet discharge variability. Sometimes, significant soil properties change (change of soil type or change in soil water content) adding a deterministic cause to the variability of the infiltration. Temporal variability of the infiltration characteristics is governed by two phenomena. The first is closely connected to soil water content (SWC) variation which is governed by the climatic demand. The second is due to the soil structure change through the irrigations. The latter, which is particularly significant in a surface irrigation context, cannot be reliably predicted (Or, 1996). Consequently the variability of the infiltration parameter, which is mainly affected by the soil structural change, cannot be modeled properly.

In order to get grips with these problems of variability and to achieve complete benefits of modeling and optimization it is necessary to model and optimize each irrigation event in real-time by using real-time predicted infiltration characteristics, and this would be possible only with a model that should be capable to process minimum field data and provide soil infiltration characteristics while the irrigation event is in progress.

## 4.5 Conclusion

The most important variable inputs in design and management of surface irrigation are the infiltration parameters. Spatial and temporal variations in these parameters complicate the situation and cause inaccuracies in their prediction. Therefore it is essential that the available infiltration estimation methods should be tested to evaluate their accuracy and ability to estimate soil infiltration characteristics under a range of inflow rates and varying furrow physical characteristics.

The soil infiltration characteristic varies substantially throughout season and across the field and has significant implications for the development of design guide lines for the management of surface irrigation practices. The multidimensional effect of various field and management parameters on the performance of surface irrigation system requires the development of design approach which may demonstrate the interaction of the various irrigation parameters and include the effect of infiltration variability. While this could be achieved through the medium of individual design charts, it could be better done through a more advanced simulation model with an in built optimization capability (Raine *et al.,* 1997). However this requires an enormous amount of field data. This high data requirement means more expense to collect data, in terms of cost, efforts and time consumption. More particularly the high data requirement hinders the implementation of any form of real-time control.

Real-time estimation of infiltration parameters, indeed, would be a better solution to overcome the infiltration variability and highly significant improvements in irrigation performance are achievable with real-time optimisation of individual irrigation events. This idea has been also supported in recent findings by Smith *et al.* (2005) who focused their study on irrigation application efficiency and deep drainage potential under surface irrigated cotton. In brief they concluded that the full gains that can be achieved through an optimisation that takes into account the temporal variability into soil infiltration characteristic could only be attainable through the implementation of some form of real-time control.

There fore under the existing situation it is necessary to develop a simple, practicable real-time control system that should have potential to process absolutely minimum field data and provide soil infiltration characteristics in real-time and without significant loss of accuracy, and be able to predict the optimum time to cut-off while the event is underway, to achieve better control and management for the most efficient performance of surface/ furrow irrigation.

# Chapter 5

# Evaluation of Methods for Determining Infiltration from the Irrigation Advance

## 5.1 Introduction

The infiltration characteristic of the soil is one of the key factors in determining the performance (efficiency and uniformity) of surface irrigation applications and exerts its influence by controlling the rate of advance of the irrigation water down the furrow or bay. This chapter presents an evaluation of the different methods for measuring this characteristic and concludes that there is a need to develop a new method which would require absolutely minimum field data and provide the soil infiltration characteristics in real-time. The material discussed in this chapter has been published as Khatri and Smith (2005).

Knowledge of the spatial average value of infiltration characteristic is required for the accurate simulation and optimisation of surface irrigation. Substantial recent work has been directed towards developing methods to measure the infiltration properties of the soil. Solution of the inverse problem has generated most interest that is, determining the infiltration parameter values from the measured surface irrigation advance.

Models used to solve the inverse problem consist of two parts. The first is an equation capable to describe process of infiltration, or entry of water into soil e.g. Kostiakov-Lewis equation which is often used. The second part of the inverse solution consists of a model representing the flow / distribution of water along the furrow or bay. This links the infiltration equation to measurable parameters such as the inflow, surface water depth and irrigation advance. This component usually takes the form of either a hydrodynamic advance model (consisting of continuity and momentum equation) or volume balance model (consisting of continuity equation only).

The volume balance equation is solved analytically to find the infiltration functions from the field advance data and can be applied at any time during the advance phase of an irrigation event. It simply states that at any time the volume of water applied to that time can be equated to the volume stored (temporarily) on the surface of furrow or bay (in the surface flow) plus the volume infiltrated to that time:

$$Q_o t = \overline{A}x + \overline{I}x \tag{5.1}$$

where $Q_o$ is the inflow to the furrow or bay; $t$ the elapsed time since the commencement of the irrigation; $X$ the distance reached by the advance in that time; $\overline{A}$ the average cross sectional area of the surface flow, over the distance $x$; and $\overline{I}$ the average cumulative volume infiltrated per unit length of furrow over that same distance.

Quantifying the two average terms gives:

$$Q_o t = \sigma_y A_o x + \int_0^x I dx \tag{5.2}$$

where $A_o$ is the cross sectional area of flow at the upstream end of the field and $\sigma_y$ is the surface storage shape factor (which has the value of 0.8).

A number of methods are available based on the volume balance model. Data requirements for the models vary considerably, and some condition or constrain the solution to reduce the requirement for data, but in ways that may limit application of the method to certain soils and situations. Many of the methods discussed here have only been tested on a limited range of soil types and conditions, typically for low flow rates in short furrows and relatively light textured soils. Hence the applicability, accuracy and robustness of the models have not been proved adequately.

The work reported here is the first part of a study directed at the development of a simple and practical real-time control system for surface irrigation. There is a requirement for an accurate and robust method for determining the infiltration characteristic from an absolute minimum of field data. Competing methods are tested for their ability to accommodate the long furrows and long irrigation durations common in northern Australia and be able to describe the infiltration characteristics of the predominant heavy clay (cracking) soils. The tension between the accuracy and reliability of each method and the data requirement is also assessed.

## 5.2 Description of methods

A description of each method, the main algorithms used and the computational procedures are presented in this section. For consistency in presentation, the symbols used in some methods have been changed from the source paper.

### 5.2.1 Two-point method

The two-point method of Elliott and Walker (1982) is presently the industry standard method for determining the infiltration characteristics of an irrigation furrow or bay from measurements of the irrigation advance. The method is a simple application of the volume balance approach that uses only two points on the advance curve, usually at the mid-distance and at the downstream end of the field.

The method assumes that the advance curve can be approximated by a simple power function:

$$x = p(t)^r \tag{5.3}$$

where $t$ is the time taken for the wetting front to reach advance distance $x$. The fitted parameters $p$ and $r$ can be evaluated from the two advance points and a simple logarithmic transformation of the power curve equation.

The infiltration function used by Elliott and Walker (1982) is the modified Kostiakov equation:

$$I = k\tau^a + f_o\tau \tag{5.4}$$

where $\tau$ is the time from the commencement of infiltration at the point where the equation is being applied. For any point $X$, $\tau = t - t_X$, where $t$ is the current time from commencement of the irrigation and $t_X$ the time that the advance reached point $X$.

Integrating the infiltration function to give the volume infiltrated in the volume balance equation (5.2) gives:

$$Q_o t = \sigma_y A_o x + \sigma_z k t^a x + \frac{f_o t x}{1+r} \tag{5.5}$$

where $\sigma_z$ is a the sub-surface shape factor, defined as:

$$\sigma_z = \frac{a + r(1-a) + 1}{(1+a)(1+r)} \tag{5.6}$$

The left hand side of equation (5.5) is the volume applied to the field, the first term on the right hand side is the volume stored on the surface and the remaining two terms make up the volume infiltrated.

Applying the volume balance equation at the two points for which we have measured the advance times gives two simultaneous equations that can be solved for the infiltration parameters $a$ and $k$.

A requirement for the solution for $a$ and $k$ is that the value of $f_o$ must be known. The preferred method for evaluating $f_o$ is the inflow-outflow method. If the irrigation is continued for a long time the runoff ($Q_{out}$) from the end of the field will reach a steady value, indicating that the infiltration at all points along the furrow or bay has reached its final value $f_o$. At this time:

$$f_o = \frac{Q_o - Q_{out}}{L} \tag{5.7}$$

### 5.2.2 INFILT

The program INFILT (McClymont & Smith, 1996) uses the same basic equations (5.3 to 5.6) as the two-point method. The method differs from the two-point method in that only advance data and inflow rates are required as input data. The average cross-sectional area of the furrow and the final infiltration rate are treated as fitted parameters and need not be measured. The most common use of the program employs 4 or more advance points to determine best fit values for the three infiltration parameters $a$, $k$ and $f_o$ (and the average cross sectional area of the flow $\sigma_y A_o$ if this term is not known).Three advance points can be used if $A_o$ is known.

By entering known values for certain of the parameters the program can:

- Emulate the two-point method if $f_o$ is known;
- Fit a Philip type infiltration equation by setting *a* to a value of 0.5; and
- Fit a linear infiltration equation (for a cracking clay soil) by giving the parameter *a* the value of zero.

Where known values are entered for any of the parameters, the minimum number of advance points required is reduced.

### 5.2.3 Valiantzas one-point method

Valiantzas *et al.* (2001) proposed a method involving a single advance point. It utilizes the same power advance equation (5.3) as the two-point method and INFILT. However, Valiantzas *et al.* described the infiltration by the USDA infiltration function:

$$I = k\tau^{\alpha} + c \tag{5.8}$$

where $k$ and $\alpha$ are fitted parameters and $c$ is a constant (0.007 $m^3$/m length).

Valiantzas *et al.* showed that $k$ and $\alpha$ are related by the function:

$$k = \frac{14088\alpha^{45} + 0.148(-\ln\alpha)^{-1.652}}{1000} \tag{5.9}$$

Substitution of (8) into the volume balance equation (2) and integrating gives:

$$Q_o t = \sigma_y A_o x + \sigma_z k t^{\alpha} x + cx \tag{5.10}$$

where $\sigma_z$ has the same definition as in the two-point method.

By using the points ($x_2,t_2$) and ($x_1,t_1$) where $t_1 = 0.5t_2$ we have two simultaneous equations to be solved for the unknown infiltration parameters, viz:

$$r = \frac{\ln(x_1/x_2)}{\ln(t_1/t_2)} = \frac{\ln\left((0.5Q_o t_2)/\left(0.5^{\alpha}\left(Q_o t_2 - \sigma_y A_o x_2 - cx_2\right) + \sigma_y A_o x_2 + cx_2\right)\right)}{\ln(1/2)} \quad (5.11)$$

and:

$$f(\alpha) = \sigma_z k t_2^{\alpha} - \frac{Q_o t_2 - \sigma_y A_o x_2 - cx_2}{x_2} = 0 \quad (5.12)$$

Solution requires an iterative procedure as follows. An initial value for $\alpha$ is estimated and $r$ is calculated from equation (11). Equation (12) is solved for $\alpha$ using a Newton-Raphson solution, viz:

$$\alpha_{new} = \alpha - \frac{f(\alpha)}{f'(\alpha)} \quad (5.13)$$

where:

$$f'(\alpha) \approx \sigma_z t_2^{\alpha}\left(\frac{dk}{d\alpha} + k \ln t_2\right) \quad (5.14)$$

and (correcting a typographical error in the paper by Valiantzas *et al.* 2001):

$$\frac{dk}{d\alpha} = 633.96\alpha^{44} + \frac{0.2445(-\ln\alpha)^{-2.652}}{1000\alpha} \quad (5.15)$$

The calculation of $r$ and $\alpha$ is repeated until the $\alpha$ values converge.

## 5.2.4 Upadhyaya and Raghuwanshi

In the derivation of their method, Upadhyaya and Raghuwanshi (1999) described the infiltration by the rate form of the exponential Horton equation. For this dissertation the method has been reworked in terms of the cumulative form of the equation:

$$I = F(1 - e^{-\theta\tau}) + f_o \tau \tag{5.16}$$

where $F$ and $\theta$ are fitted parameters, and $f_o$ has its usual meaning. The parameter $F$ is a function of the initial and final infiltration rates.

The advance is described by an exponential equation:

$$x = x_{\max}(1 - e^{-\theta t}) \tag{5.17}$$

where it is assumed that the exponent $\theta$ is the exponent in the Horton equation, $x_{max}$ is the maximum possible advance distance (stalling point), and the steady or final infiltration rate $f_o = \dfrac{Q_o}{x_{\max}}$ (5.18)

Substitution of equation (5.16) for $I$ in the volume balance equation (2) and integration gives the final volume balance equation as:

$$Q_o t = \sigma_y A_o x + Fx - F(x_{\max} - x)\theta t + f_o x_{\max} t - \frac{f_o x}{\theta} \tag{5.19}$$

Once equation (5.17) has been fitted to the advance data to give $x_{max}$ and $\theta$, the two infiltration parameters $f_o$ and $F$ can be calculated directly from equations (5.18) and (5.19), respectively.

### 5.2.5 Linear infiltration

A simple linear infiltration function has been used previously by Austin and Prendergast (1997) and Mailhol *et al.* (1997). It is applicable to cracking clay soils, which exhibit a unique infiltration characteristic consisting of an instantaneous crack fill followed by a steady rate of infiltration. It assumes an infiltration equation of the form:

$$I = Z_{CR} + f_o \tau \qquad (5.20)$$

where $Z_{CR}$ is the crack fill term.

In this dissertation a very simple approach is followed that employs the same volume balance equation (5.2) and power advance trajectory equation (5.3) as INFILT and the two-point method to give the equation:

$$Q_o t = \sigma_y A_o X + Z_{CR} X + \frac{f_o t X}{1+r} \qquad (5.21)$$

The exponent $r$ in the power advance is determined from two advance points as in the two-point method and the same two advance points are used in equation 5.21 to give two simultaneous equations to be solved for the two unknowns $Z_{CR}$ and $f_o$.

### 5.2.6 Shepard one point method

Shepard *et al.* (1993) developed a simple one-point method by over-conditioning the problem in two ways. First they assumed a simple power curve advance (eqn 5.3) in which the exponent $r$ was constrained to a value of ½. Second they used the Philip infiltration equation (Philip and Farrell, 1964).

$$I = S\tau^{1/2} + A\tau \qquad (5.22)$$

where $S$ and $A$ are usually taken as physically based variables but in this particular application they are by implication empirical parameters. When taken as an empirical equation this is the same as using the modified Kostiakov equation but with the exponent $a$ set to the value of ½. In that case $S$ is equivalent to the Kostiakov $k$ and $A$ to the final infiltration rate $f_o$.

Substitution into the volume balance equation gives:

$$Q_0 t = \sigma_y A_o x + \frac{\pi S}{4} x t^{1/2} + \frac{2A}{3} x t \tag{5.23}$$

Knowing that $x_1 = x_2/2$ and $r = ½$ gives:

$$A = \frac{3\sigma_y A_o}{t_2} \tag{5.24}$$

and

$$S = \frac{4(Q_o t_2 - 3\sigma_y A_o x_2)}{\pi t_2^{1/2} x_2} \tag{5.25}$$

Using the single advance point ($x_2$, $t_2$), equations 5.24 and 5.25 are solved for the infiltration parameters $A$ and $S$.

## 5.3 Evaluation

### 5.3.1 Test data

The above methods were evaluated for 10 furrow irrigation events conducted by growers using their usual practices. These events were selected from the over 300 individual furrow irrigation events conducted across the cotton growing areas of southern Queensland and the sugar areas of north Queensland for which irrigation water balance and irrigation advance data have been collected.

Data collected for each event included:

- furrow inflow rates (and outflow for events D3 and D4 only);
- irrigation advance (advance times for various points along the furrow including the time for the advance to reach the end of the furrow);

- physical characteristics of the furrow (slope (D4 and D7 only), length, and cross section shape).

The flow rate and irrigation advance were measured using the IRRIMATE™ suite of tools developed by the National Centre for Irrigation in Agriculture (NCEA), as described by Dalton *et al.* (2001). The 10 data sets are summarized in Table 5.1 and the full advance data set are shown in Appendix A.

**Table 5.1 showing summary of data sets**

| Data Set | Soil Type* | Flow rate (l/s) | Length (m) | Advance time (min) |
|---|---|---|---|---|
| D1 | Grey vertosol | 4.44 | 625 | 577 |
| D2 | Red light sodosol | 5.0 | 240 | 277 |
| D3 | Yellow sodosol | 2.01 | 1200 | 2523 |
| D4 | Sodosol | 1.29 | 800 | 735 |
| D5 | Black vertosol | 7.67 | 750 | 441 |
| D6 | Sodic grey vertosol | 1.96 | 725 | 416 |
| D7 | Black vertosol | 4.02 | 882 | 1349 |
| D8 | Red sodosol | 3.6 | 625 | 440 |
| D9 | Sodic grey vertosol | 2.93 | 608 | 289 |
| D10 | Grey vertosol | 6.62 | 700 | 558 |

*Soils described according to Isbell (1996)

### 5.3.2 Analysis

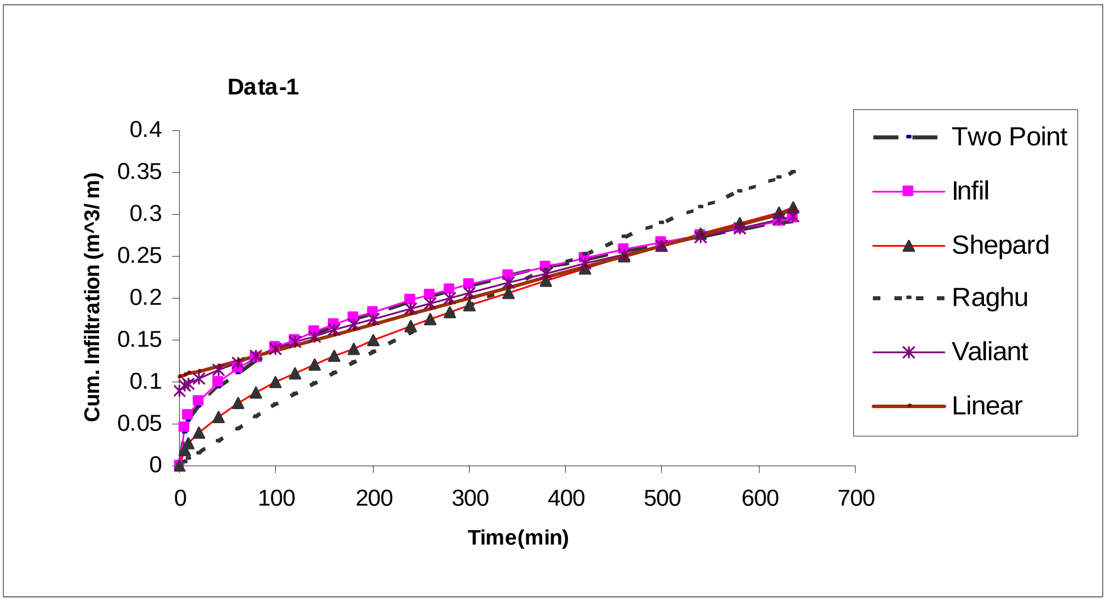
Spreadsheet programs were developed for each of the methods, to determine the infiltration parameter values given by each method for the different data sets and hence the cumulative infiltration curves. The exception was INFILT where the proprietary software package was used. The spread sheet printouts are provided in Appendix A.

To evaluate the accuracy of the infiltration estimates, advance curves were predicted using the infiltration parameters and the volume balance equations for each method, with advance times as the unknown. These predicted advance curves were then compared to the measured advance curves.

## 5.4 Results and Discussion

The predicted cumulative infiltration and advance curves are presented in Figures 5.1 and 5.2, respectively. It should be noted here that advance data only was used to determine the infiltration parameters. This places severe limits on the time over which the infiltration estimates are valid. Extrapolation of the functions beyond that time may result in substantial error in predictions of infiltrated depths and volumes. However each of the methods is affected equally by this limitation.

Each of the methods requires estimates of the volume of water temporarily stored on the soil surface at various times. This confers another limitation on the infiltration estimates. This is particularly so for short furrows, where the advance trajectories are more a function of the surface storage characteristics of the furrow rather than of the infiltration properties (Philip and Farrell, 1964). Since the magnitude of the surface volume relative to the total volume applied diminishes with time, those errors have a lesser impact on the estimation of infiltration. This is a substantial benefit in the relatively long furrows used in Australia and with their very long irrigation durations.



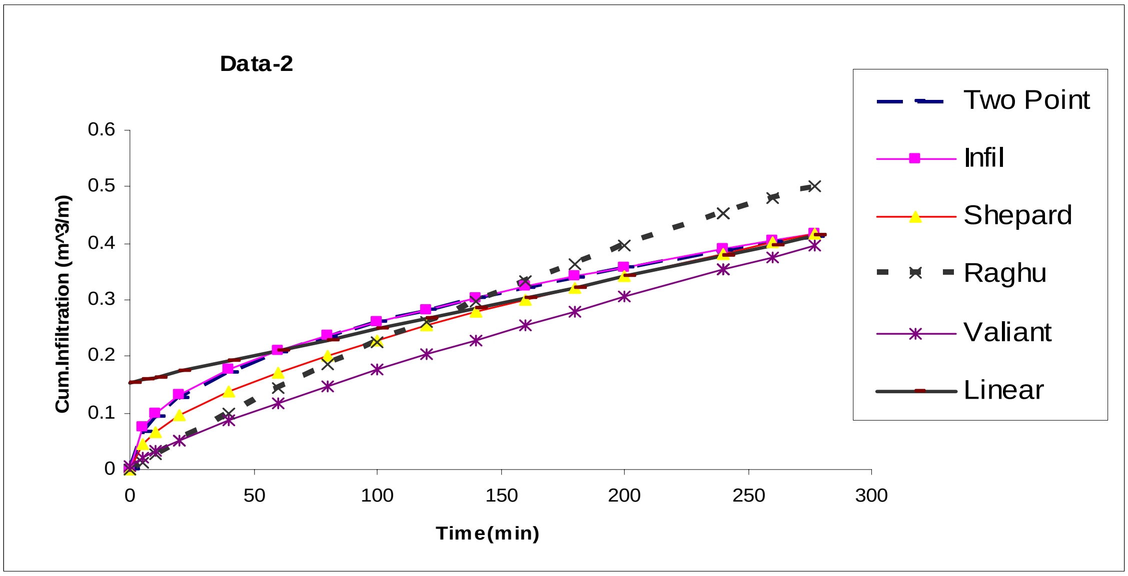
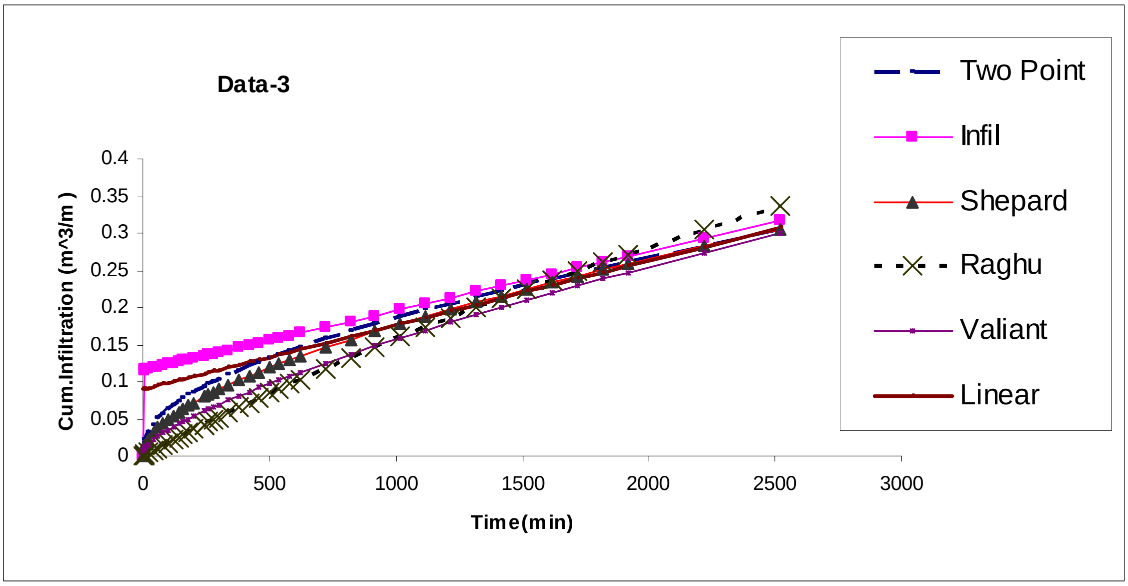




**Figure 5-1 Comparison of cumulative infiltration curves**



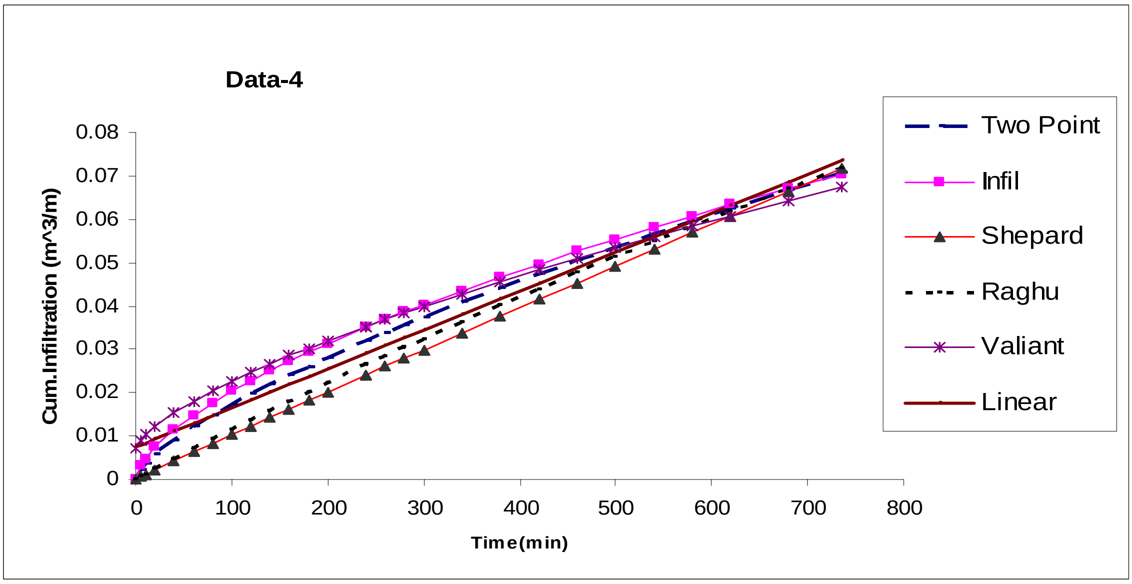
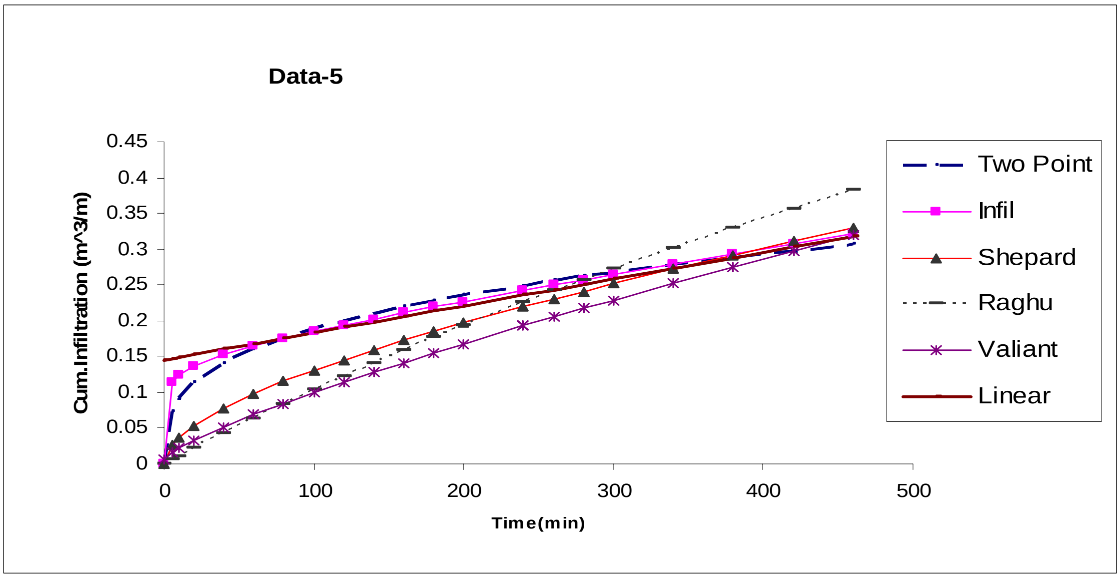




**Figure 5.1 Comparison of cumulative infiltration curves (continued)**



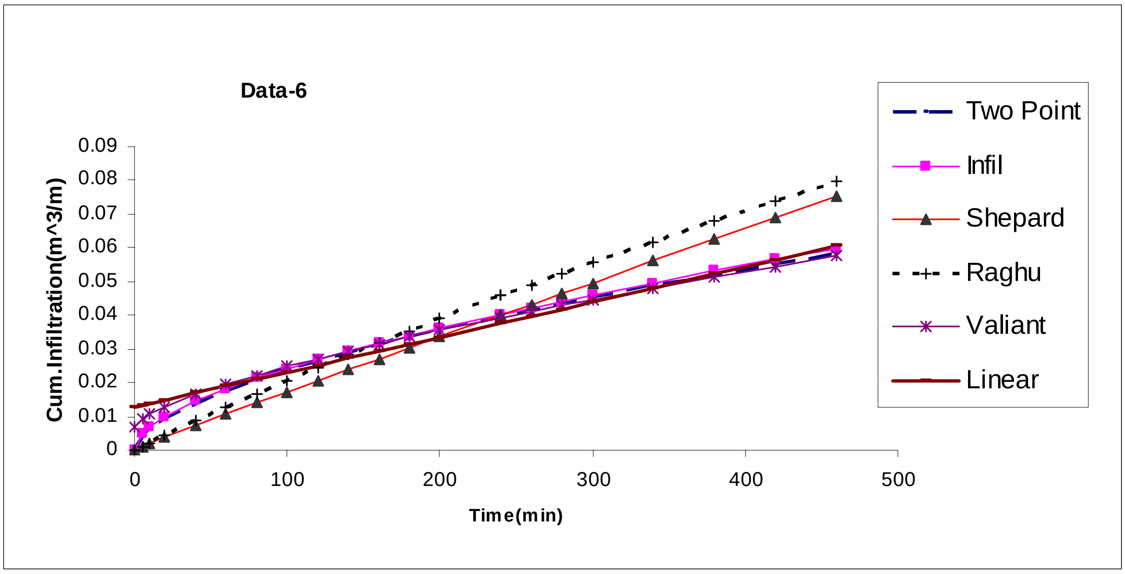
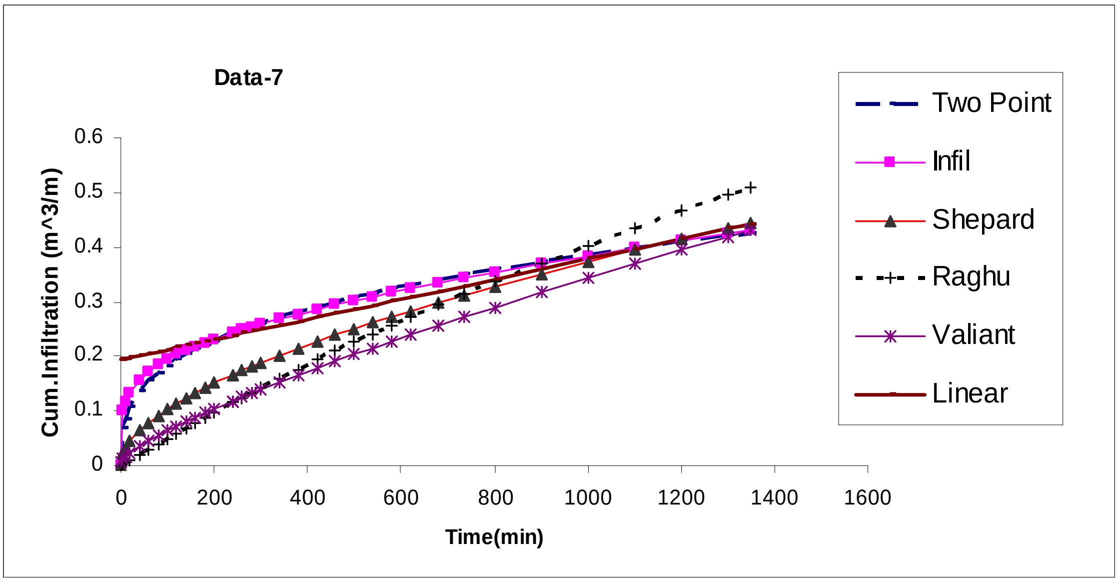




**Figure 5.1 Comparison of cumulative infiltration curves (continued)**



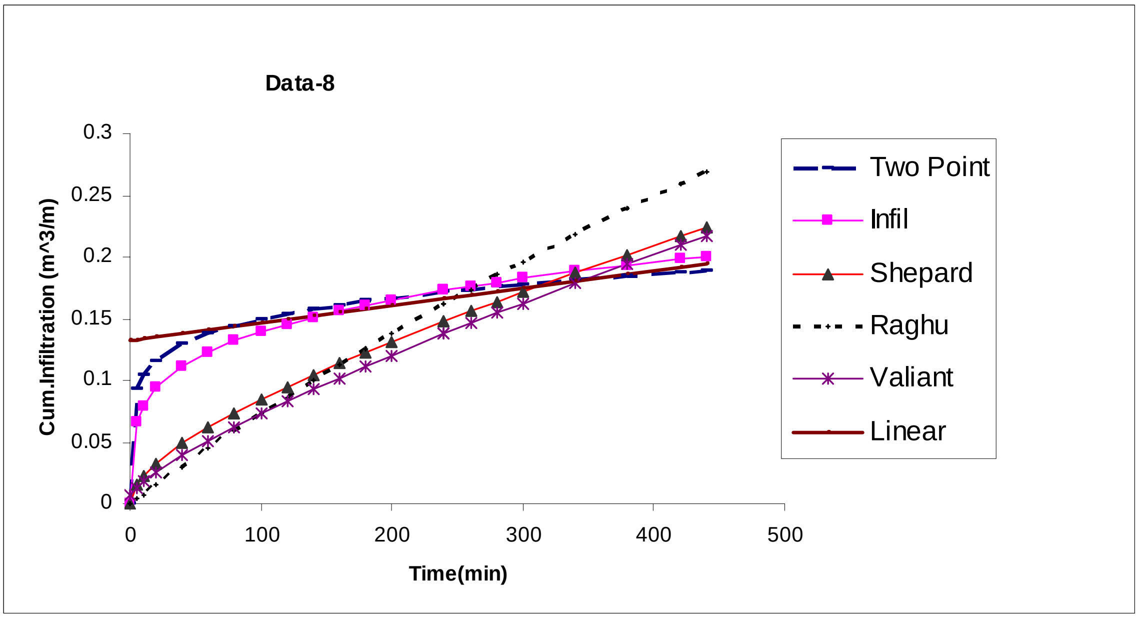
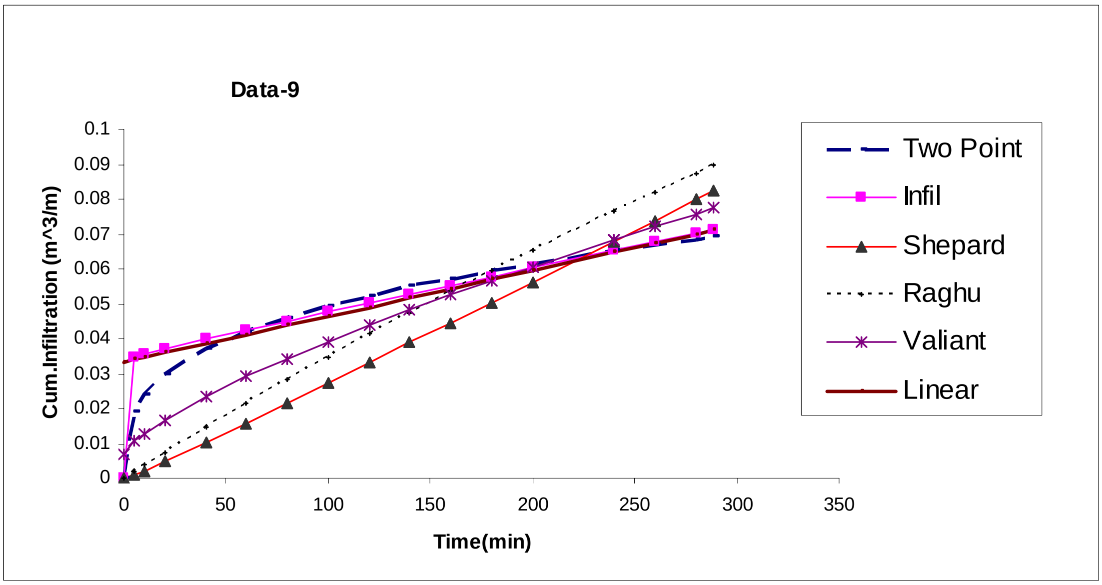




**Figure 5.1 Comparison of cumulative infiltration curves (continued)**



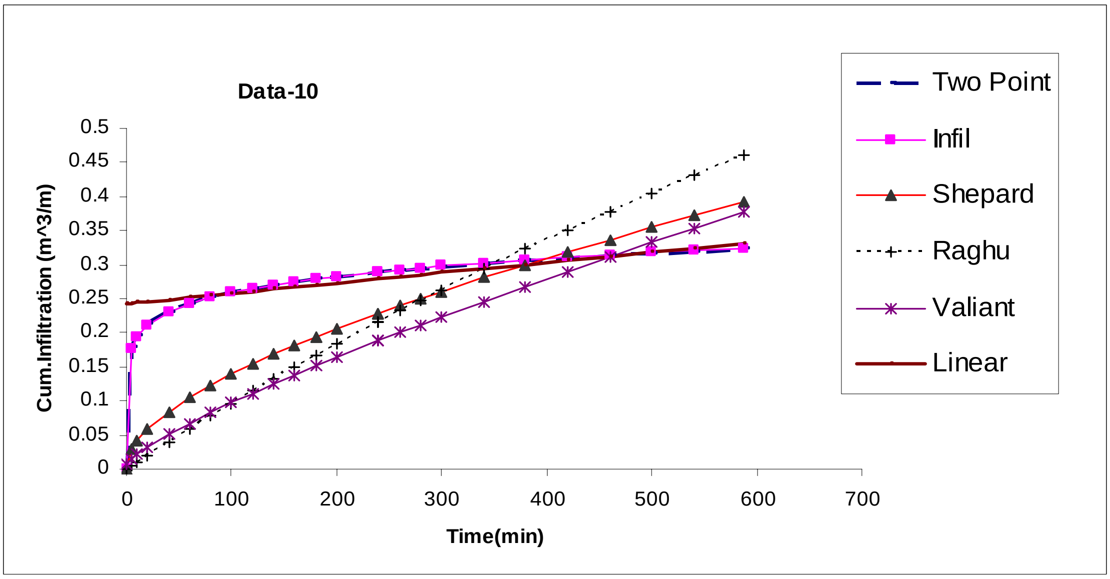
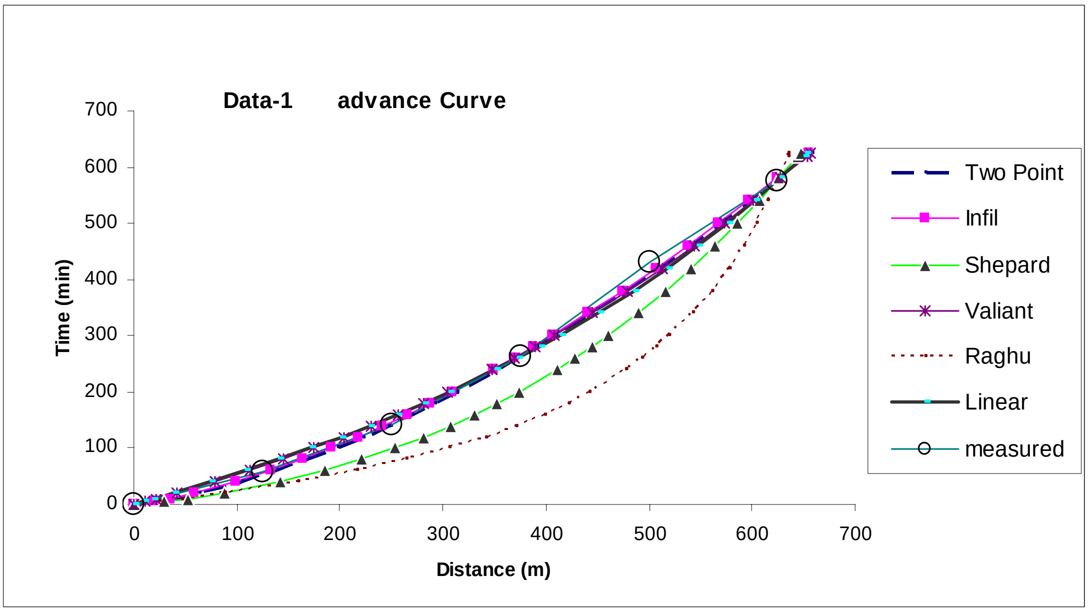




**Figure 5.1 Comparison of cumulative infiltration curves (continued)**



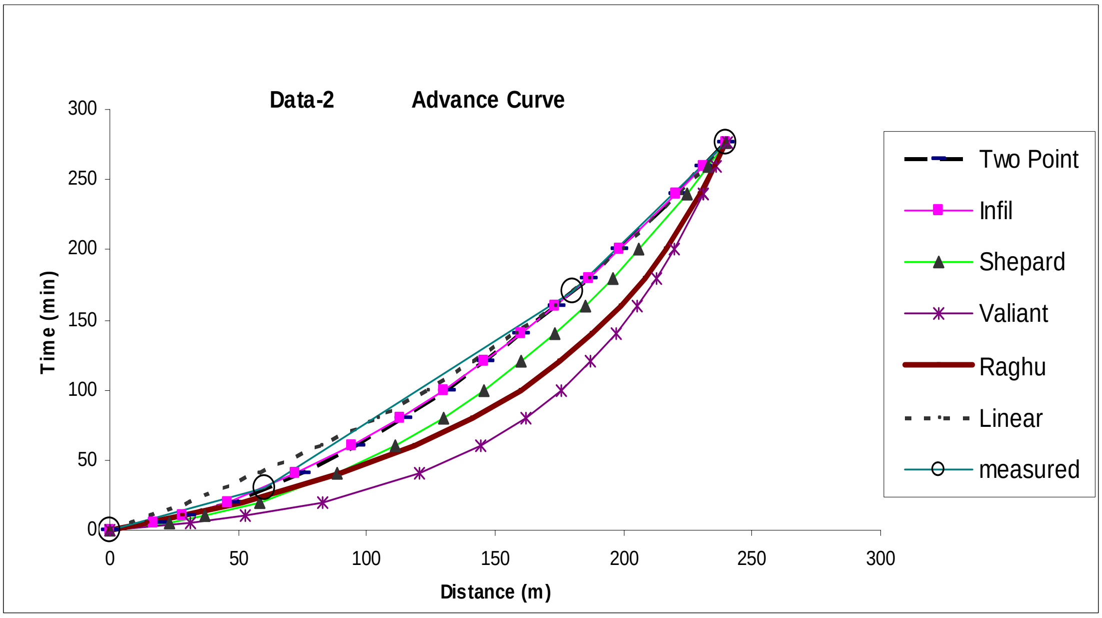
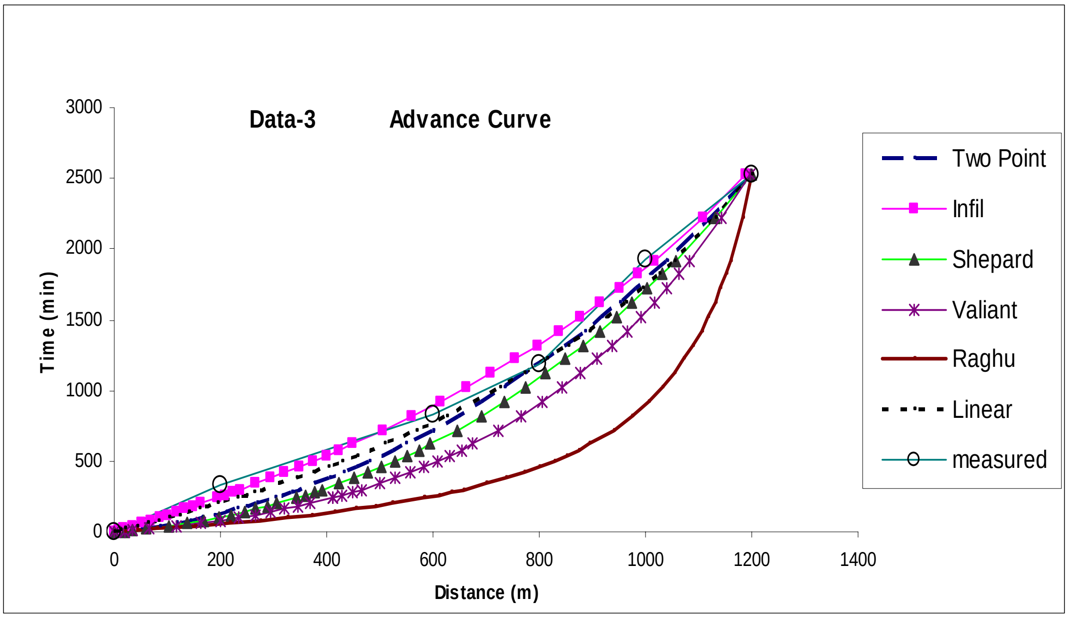




**Figure 5-2 Comparison of advance curves**



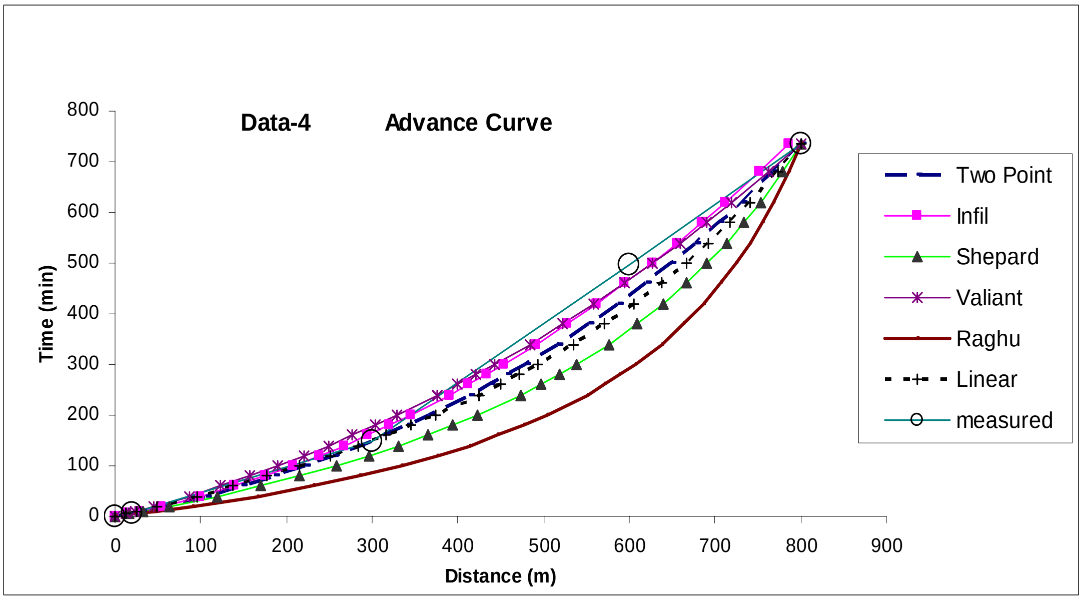
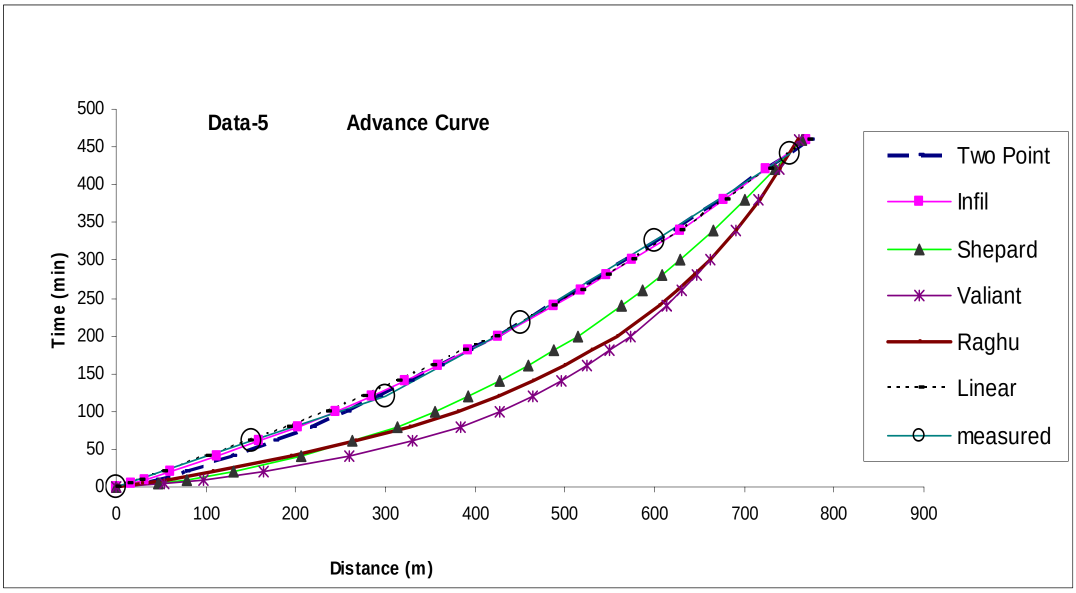




**Figure 5.2 Comparison of advance curves (continued)**



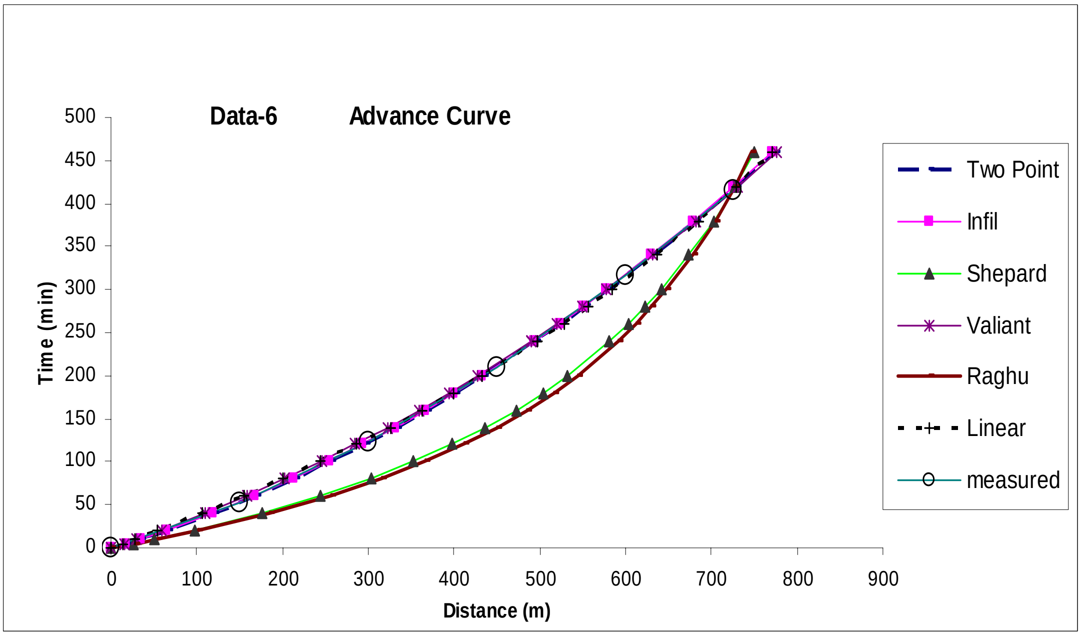
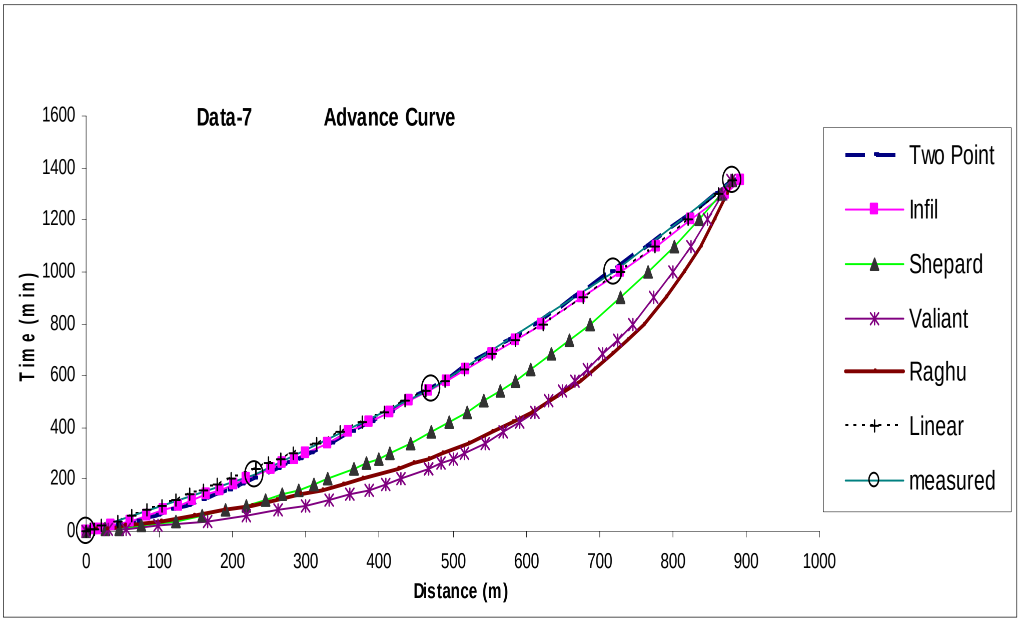




**Figure 5.2 Comparison of advance curves (continued)**



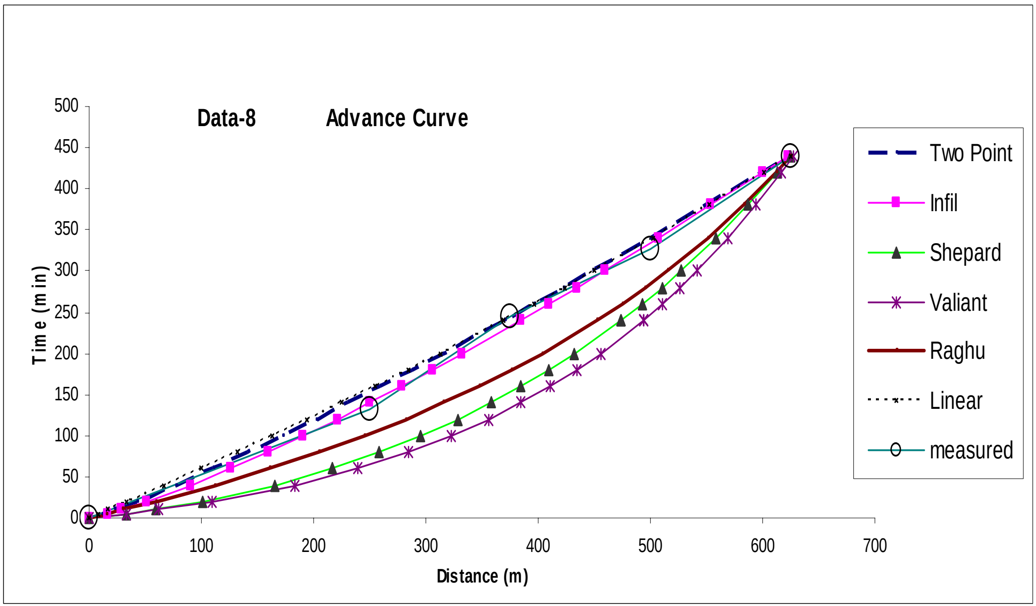
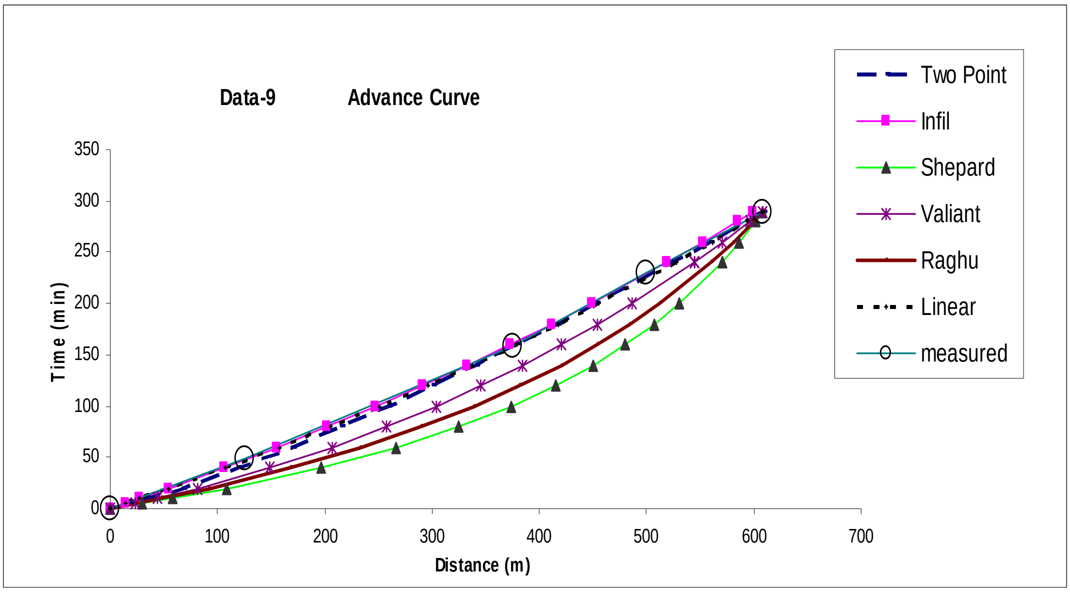




**Figure 5.2 Comparison of advance curves (continued)**



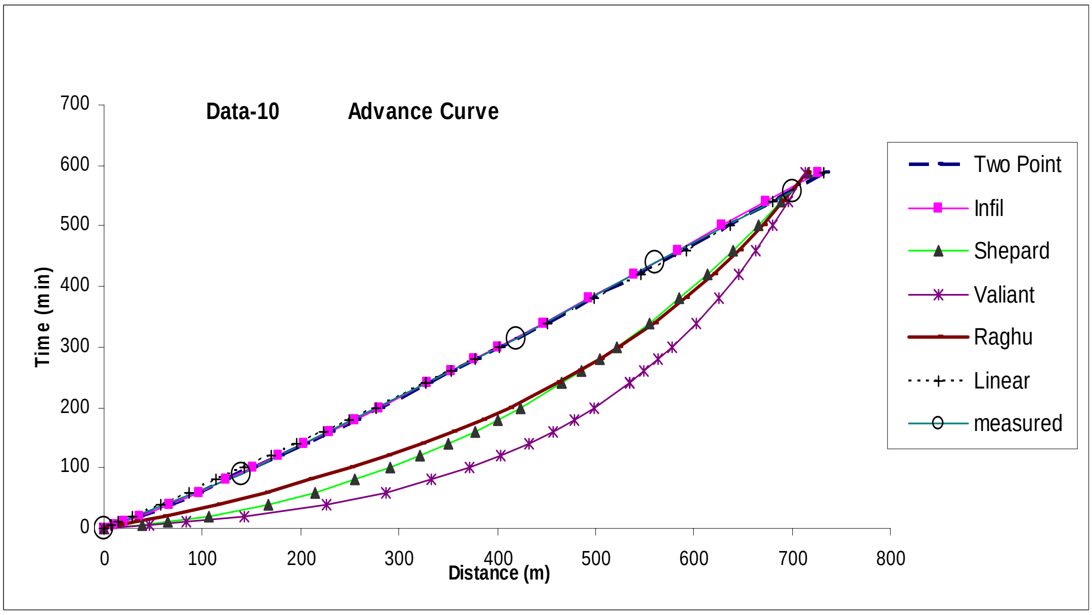




**Figure 5.2 Comparison of advance curves (continued)**

From these curves it can be seen that all models except that of Upadhyaya and Raghuwanshi give similar estimates of the cumulative infiltration at times equal to the advance time for each trial. However, the shapes of the infiltration curves vary considerably. Similarly all of the predicted advance curves converge on the final advance points but some methods consistently return advance trajectories of very different form to the measured curves. The results and the performance of each method are discussed below. The results for infiltration parameters obtained under each method are shown in Appendix 3.

### 5.4.1 Two-point method

During this study the two-point method has been used as the benchmark model because of its proven performance over time and over a range of soils and situations**.** The advance trajectories predicted by this method show good reproduction of the measured advance in all cases (as shown in Figure 5.2). In the two cases D3 and D4, the measured advance curves were irregular. Selection of a different advance point as the first advance point would have given a slightly different result for the infiltration parameters and for the predicted advance curve.

Outflow data was available, and hence the final infiltration rate *($f_o$)* was calculated for only two data sets, D3 and D4. In all other cases $f_o$ was assumed to be zero. This is not an unreasonable assumption because most of the soils were heavy clay soils (except D2 which is a high infiltration soil) for which the $f_o$ is low or near zero. Consequently the method works well up to the advance time, but is likely to under predict cumulative infiltration at longer times (in extra polation case), for example, as seen in Figure 5.3.

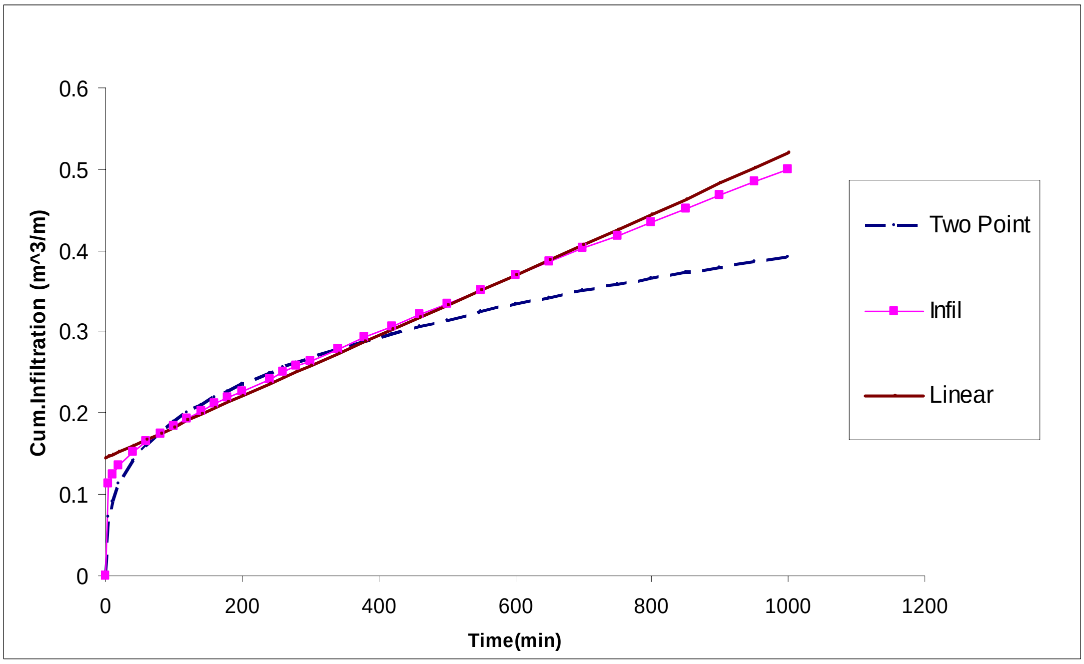



**Figure 5-3 Cumulative infiltration for longer times (advance time is 441 min).**

In summary, and despite the above qualifications, the two-point method was effective across all soil types included in the study. Although only two advance points are required the method still remains information expensive in that the basic infiltration rate must be measured separately. Errors in the measurement of $f_o$ can lead to inaccuracies in the infiltration parameter values, for example, in Serralheiro (1995) where overestimates of $f_o$ led to negative values of the exponent $a$ in the infiltration function.

## 5.4.2 INFILT

As would be expected, this method predicts cumulative infiltration curves very similar to the two-point method in all cases as shown in Figure 5.1. Excellent reproduction of the advance curves (closest to measured) in all data sets proves the suitability and ability of the model to perform well over the range of different soils and situations studied.

This method has advantage of not requiring previous knowledge of the final infiltration rate ($f_o$), and because it uses all available advance points it can handle poor quality (irregular) advance data, for example, D3 and D4. The inclusion of the final infiltration rate ($f_o$) as an empirical parameter is only likely to become a problem with high infiltration soils involving short advance times. Under these circumstances the predicted value may be much lower than the true physical value and may tend to zero (McClymont *et al.*, 1996). This difficulty arises due to inability of the method to differentiate between the time variant and steady state components of infiltration for the short advance times. This observation agrees with Bautista and Wallender (1993) who found that the reliability of parameter estimates increased for relatively long advance times. Despite this limitation the model performed well on the one high infiltration soil (D2) included in this study.

The model has also shown a good ability to determine the infiltration parameters for cracking clay soils as demonstrated in the case of D5 and D9 in Figures 5.1 and 5.2. In the case of D3 (yellow sodisol), INFILT returns a characteristic typical of a cracking soil when the other methods give what appear to be more realistic results for that soil. However, the INFILT curve still manages to reproduce the advance trajectory better than those from the other methods.

The disadvantage of INFILT is that it requires minimum three advance points for good prediction of infiltration. In this and many other respects INFILT is similar to the three-parameter model of Mailhol *et al.* (1997) although its performance is limited to a small degree by the use of the power curve advance function.

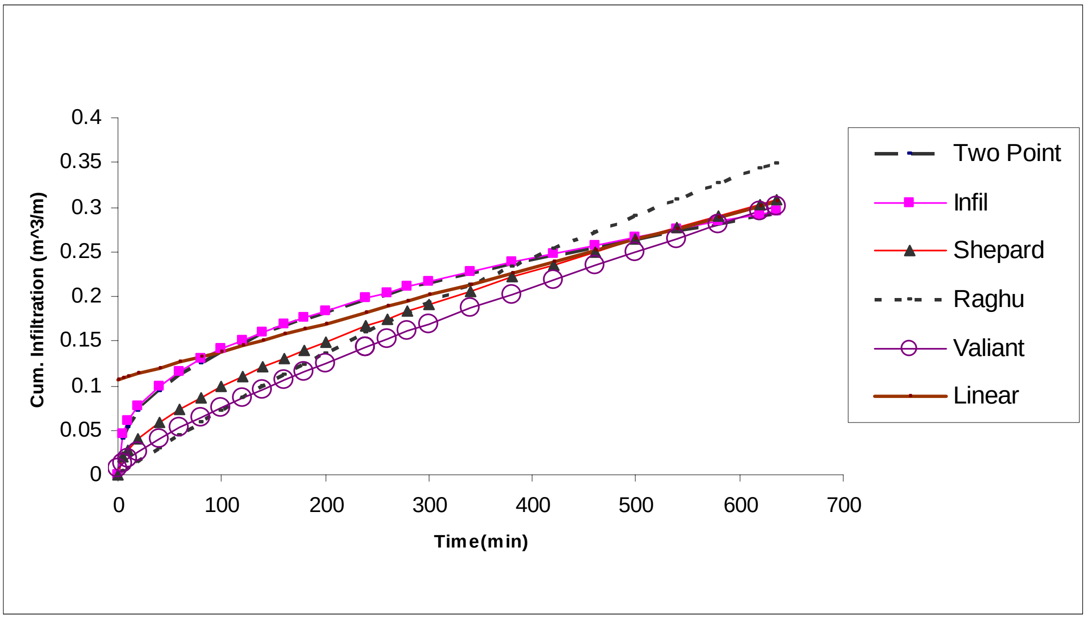
### 5.4.3 Valiantzas one-point method

Valiantzas *et al.* (2001) constrain the solution by assuming the SCS infiltration equation with its constant value for parameter $c$. For all data sets except for D6 this model underestimates cumulative infiltration up to the advance time and gives a poor reproduction of the advance curves. Only data set D6 has an infiltration characteristic compatible with the SCS curves.

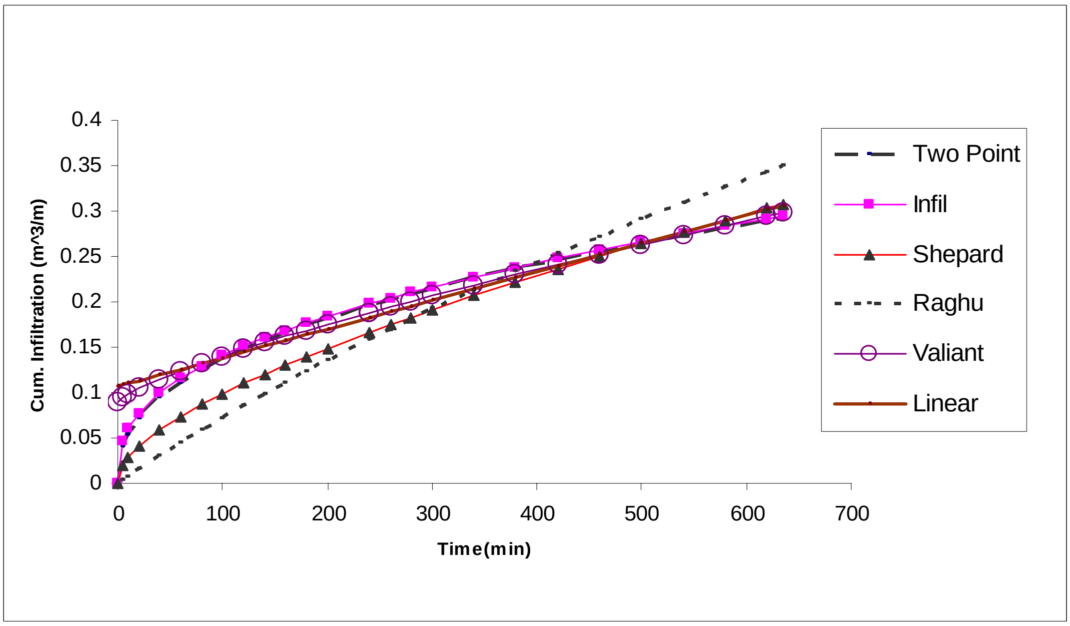
The analysis has shown that the equation cannot describe the high infiltration rates (mostly crack fill) at the very early times evident for most for the soils included in this study. The problems in the model appear to be with the constant value of 0.007 for $c$ and with the fixed relationship between the parameters $k$ and $\alpha$.

When the value of the parameter $c$ was included in the optimisation, and allowed to vary (resulting in values ranging from 0.07 to 0.198), the performance of the method was improved significantly. The subsequent cumulative infiltration plots and advance trajectories were very similar to the benchmark model (the two-point method), as shown for the case of data set 1 (D1) in Figure 5.4.

A potential additional problem with the Valiantzas method is its reliance on a single advance point. While reducing the data requirements is a desirable attribute, it relies on the single advance point used for the infiltration prediction being accurate and representative of the whole advance curve.




**(a) When C=0.007**




**(b) When C=0.09**

**Figure 5-4 Effect of varying the value of C in SCS equation**

### 5.4.4 Upadhyaya and Raghuwanshi

In almost all cases, the model of Upadhyaya and Raghuwanshi (1999) under-estimates the cumulative infiltration at early times and over-estimates it at longer times as shown in Figure 5.1. Reproduction of the advance curves is poor in all cases (Figure5.2).The most likely cause of this poor performance is in the equation assumed for the advance curve. It can be argued that an exponential curve can represent the advance trajectory more accurately than can a power curve. However, while it has been shown by Renault and Wallender, 1992 and Mailhol *et al.* (1997) that the exponent in the advance curve is related to the exponent in the infiltration equation, Upadhyaya and Raghuwanshi (1999) have not provided evidence that they should be equal. The result is that, with the relatively flat advance trajectories for the soils in this study, the model overestimates the final infiltration rate ($f_o$).

It should also be noted that when proposing the method, Upadhyaya and Raghuwanshi (1999) presented a less than convincing validation. Despite being tested in conditions favourable to the model (short furrows and permeable soil), furrow discharges predicted using the volume balance equation and the calculated infiltration parameters showed considerable deviation from the measured values.

### 5.4.5 Linear infiltration

A linear infiltration function requires less data than INFILT and the two-point method. It has given a reasonable representation of the cumulative infiltration curve for most data sets (Figure 5.1), but as expected performed worst on the soils that exhibited most curvature in the infiltration characteristic and those that exhibited least cracking, for example, (D4) data set 4.

The model gave a good reproduction of the advance curves that matched well with the measured advance curves and those generated from the benchmark model, as evident in Figure 5.2. While not as versatile as INFILT, this method requires only two advance points and gives acceptable results for the range of Queensland soils studied. This and its simplicity suggest it might provide the basis for a real-time control system.

### 5.4.6 Shepard one-point method

The model of Shepard *et al.* (1993) constrains the solution by assuming that the exponent $r$ in the power advance equation is equal to ½ and by using the Philip infiltration equation. Because of this the method fails in all cases to give a reasonable prediction of the cumulative infiltration or to reproduce the measured advance curves. From Figure 5.1, it is evident that this model is under predicting cumulative infiltration at all times up to the final advance time. The method performed best on the more permeable soil of D2.

Shepard *et al.* (1993) had previously tested the method successfully on a field in the San Joaquim Valley, California, with soils ranging from sand to clay loam. However, it is clear that the assumptions in this model are not applicable to the Queensland soils analysed under this study, particularly it is the inability of the Philip equation to cater for the rapid early time infiltration on these soils.

## 5.5 Conclusions

Methods for determining the infiltration characteristic from measurements of the furrow irrigation advance were tested on data from 10 irrigation events on heavy clay soils in the Queensland cotton and sugar growing areas.

The program INFILT was shown to be the most accurate and versatile method. It was rated ahead of the previously favoured two-point method because prior measurements of the steady infiltration rate are not required. This more than compensates for the additional advance points required by INFILT.

The linear infiltration function was shown to provide a reasonable description of the infiltration characteristics of most of the soils studied. The reduced data requirement compared with INFILT and the two-point method makes it worthy of further consideration.

The method developed by Upadhyaya and Raghuwanshi was shown to be unsuitable for the soils used in this study. The exponential representation of the advance trajectory offers considerable potential over the power curve but the relationship between the exponent in the infiltration function and that in the advance function needs further exploration.

The one-point methods of Valiantzas and Shepard *et al.* were also not suitable on the soils studied. Over-conditioning of the solution in both cases renders them inappropriate for the heavy often cracking clay soils of this project.

Finally none of the methods tested were entirely suitable for use in a real-time control system where the requirement is for applicability to a wide range of soils and minimum advance data preferably obtained early in the irrigation. However, INFILT and the linear infiltration function have the potential to be used in the real-time control provided a sufficient number of advance points are obtained.

It is therefore a pressing need to develop a new technique or model which may require one advance point and possibly to the half way down the field / furrow and provide infiltration parameters in real-time and without significant loss of accuracy. This would provide equipment and labour cost advantages by enabling the sensor (water advance sensor) to be left in the field throughout the whole irrigation season (as opposed to only 1 to 3 irrigations per season at present). The use of fewer in-field sensors means that it would be a cost effective and rapid tool in providing data for real-time control and optimization of surface irrigated fields.

# Chapter 6

# Model for Real-time Prediction of Soil Infiltration Characteristics

## 6.1 Introduction

The spatial and temporal variations commonly found in the infiltration characteristic for surface irrigated fields are a major physical constraint to achieving higher irrigation application efficiencies. Substantial work has been directed towards developing methods to estimate the infiltration characteristics of soil from irrigation advance data. However, none of the existing methods are entirely suitable for use in real-time control. The greatest limitation is that they are data intensive and hence not capable to cope with infiltration variability in real-time. A real-time control system can overcome the spatial and temporal variations and a significant improvement in performance is achievable with real-time optimisation of individual irrigation events.

Surface irrigation, especially furrow irrigation, is one of the most commonly used methods for irrigating crops and pastures in Australia and around the world due to the low cost, low energy requirements and improved aeration of the root zone. Current evaluations for furrow systems require up to five in-field advance sensors located along the furrow length. Estimates can be further improved by inclusion of runoff data (Gillies & Smith 2005). The cost, installation and download of these sensors are significant components of the current data acquisition burden. More particularly the high data requirement is a major hindrance against the implementation of any form of real-time control. There appears to be some potential to reduce the amount of data required to determine the event-specific infiltration characteristic and characterise the general infiltration equation by using a process of scaling. This approach formulates the relevant equation with the smallest possible number of variables and generalizes an infiltration equation for a broad range of applications.

Youngs and Price (1981) scaled the one-dimensional vertical infiltration into a range of soil materials with particles of different shapes and sizes. Warrick *et al.* (1985) used scaling to generalize the Philip quasi-analytical solution for one-dimensional infiltration. Warrick and Hussein (1993) used scaling techniques for the Richards equation of infiltration. Nachabe (1996) achieved a generalized numerical solution in terms of infiltration rate for one dimensional cases by scaling the *$\theta$- based* (where $\theta$ is the soil volumetric water content) form of the Richards equation. Wu and Pan (1997) presented a generalized solution to infiltration from single-ring infiltrometers also by scaling. On the other hand, some researchers made an effort to present a general equation for infiltration in furrow irrigation. They looked at modified Kostiakov equation and attempted to introduce a factor such as inflow-rate, saturated and initial soil moisture content or wetted perimeter to generalize it. Sepaskhah and Afshar (2002) presented a general infiltration equation for furrow irrigation by multiplication of $Q^{\gamma}$ (where $Q$ and $\gamma$ are the inflow rate and an arbitrary exponent respectively) in the Kostiakov-Lewis equation.

Finding a generalized solution for two-dimensional infiltration in furrow irrigation by scaling is a very useful way of reducing field data measurements required for prediction of the infiltration from irrigation advance. The work reported in this dissertation is directed towards the development of a simple and practical real-time control system for surface irrigation. Optimal surface-irrigation management requires accurate infiltration-parameter estimates. Moreover, infiltration evaluation in real-time is desirable because soil properties are spatially and temporally variable (Bautista & Wallender 1993).

A new method REIP (Real-time estimation of infiltration parameters) that uses a model infiltration curve (MIC) is proposed in this dissertation. In this method a scaling process is used to reduce the amount of data required to predict the infiltration characteristics for each furrow and each irrigation event for a whole field. The proposed method uses minimum field data (inflow and one advance point) and provides infiltration characteristics in real-time, without significant loss of accuracy, and is applicable to a broad range of soils. This work has been published as Khatri and Smith (2006).

Data from 44 furrow irrigation events from two different fields were used to evaluate the proposed method. Infiltration characteristics calculated using the proposed method were compared to values calculated from the full advance data using the INFILT computer model. The infiltration curves calculated by the proposed method were of similar shape to the INFILT curves and gave similar values for the cumulative infiltration up to the irrigation advance time for each furrow. More importantly the statistical properties of the two sets of infiltration characteristics were similar. This suggests that they would return equivalent estimates of irrigation performance for the two fields and that the proposed method could be suitable for use in real-time control.

## 6.2. Description of the Proposed Model REIP (Real-time estimation of infiltration parameters)

The underlying hypothesis for the method is 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. For the purpose of real-time control, the data required for obtaining soil infiltration characteristics for the irrigated furrows are reduced by scaling the infiltration parameters from an infiltration curve of known shape and one advance point measurement in each furrow. In this process a model infiltration curve (MIC), a new concept, is introduced. A furrow in the field is selected as the model furrow and its infiltration parameters are calculated from extensive advance and run-off data. Any infiltration equation can be used however for consistency with available simulation models the present study employs the Kostiakov-Lewis equation:

$$I = k\tau^{a} + f_{o}\tau \tag{6.1}$$

where $I$ is the cumulative infiltration (m$^3$/m),

$a$, $k$, and $f_o$ (m^3/min/m) are the fitted parameters, and

$\tau$ is the infiltration time (min).

The cumulative infiltration curve calculated from these parameters is the model infiltration curve. Subsequently the model infiltration parameters can be used to estimate (by scaling) the cumulative infiltration curves for the whole field, and other irrigation events, using only one advance point for each of the remaining furrows or for each subsequent irrigation event.

In this method a scaling factor ($F$) is formulated for each furrow or event from a re-arrangement of the volume balance model (as used by Elliot and Walker (1982) and McClymont and Smith (1996)):

$$F = \frac{Q_o t - \sigma_y A_o x}{\sigma_z k t^{a} x + \dfrac{f_o t x}{1+r}} \tag{6.2}$$

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 U/S end of furrow (m$^2$) (determined by any appropriate method),

$a$, $k$, $f_o$ are the infiltration parameters of the model furrow,

$\sigma_y$ is a surface shape factor taken to be a constant (0.77),

$\sigma_z$ is the sub-surface shape factor for the model furrow, defined as:

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

$r$ is the exponent from power curve advance function $x = p(t)^r$ for the model curve,

$t$ (min) is the time for the advance to reach the distance $x$ (m) for the corresponding furrow.

This scaling factor ($F$) is then applied in conjunction with the Kostiakov–Lewis infiltration model to scale the infiltration curves for the whole field (hereafter called the scaled infiltration curves) as follows:

$$I_s = F(k\tau^a + f_o\tau) \tag{6.3}$$

where: $I_s$ is the scaled infiltration ($m^3/m$),

$a$, $k$, $f_o$ are the infiltration parameters of the model furrow.

The scaling factor $F$ as given by equation (6.2) can be defined as the ratio between the infiltrated volume as calculated by a volume balance in the trial furrow at $t_{50}$ and the infiltrated volume as calculated by the parameters for the model furrow. The application of the factor (equation 6.3) follows from this definition and assumes each part ($k$ and $f_o$) of the infiltration function be scaled in the same proportion. If for a particular soil type either of these parameters was considered to be constant and only the other part of the infiltration function was to be scaled, a different formulation of the volume balance equation (6.2) would be required.

For the proposed real-time control system the infiltration estimates are required in sufficient time to allow selection and application of optimum times to cut-off while the irrigation event is under way. To achieve this, the advance times ($t_{50}$) taken at or near the mid-point down the furrow/field ($x_{50}$) are used in equation 6.2.

## 6.3. Testing / Evaluation of Model

### 6.3.1 Evaluating soil infiltration characteristics

The proposed method was tested and evaluated using data from 44 furrow irrigation events on two cotton fields (27 events for field T consisting of 3 irrigations on 9 furrows and 17 events for field C consisting of 4 irrigations on 3 furrows and 5 irrigations on fourth one furrow), irrigated by the growers using their usual practices. These fields were selected from the different farms across the cotton growing areas of southern Queensland for which irrigation water balance and irrigation advance data have been collected. The basis for selection was the relatively large number of events for each field.

Data collected for each event included the:

- furrow inflow rate;
- irrigation advance (advance times for various points along the furrow including the time for the advance to reach the end of the furrow); and
- physical characteristics of the furrow (length, slope, cross section shape).

The flow rate and irrigation advance were measured using the IRRIMATE™ suite of tools developed by the National Centre for Engineering in Agriculture (NCEA), as described by Dalton *et al.* (2001). The data are summarised in Tables 6.1 and 6.2, and full data sets are given in Appendix B for fields T and C, respectively.

# Table 6.1 Summary of data sets for field T

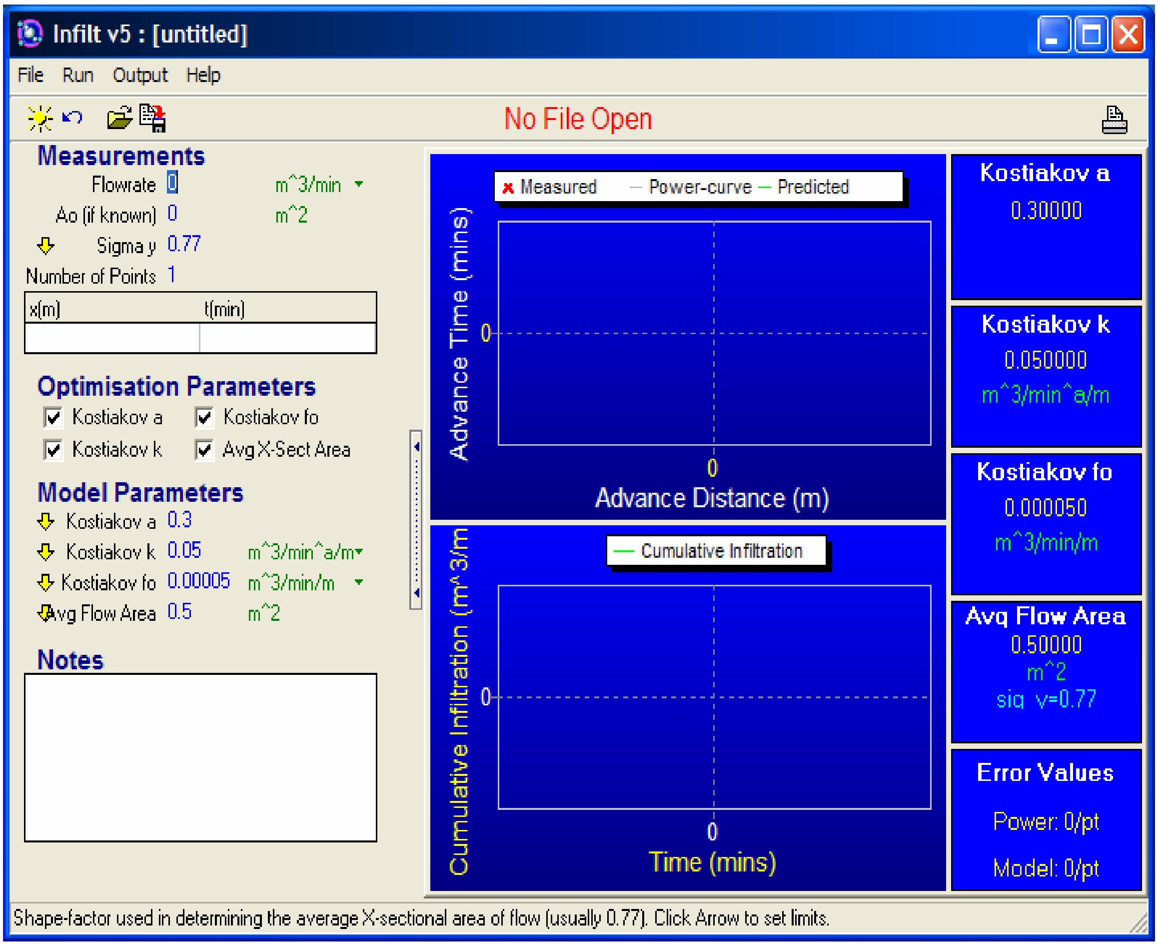
| Furrow | Length (m) | Cross-sectional area ($m^2$) | Flow rate ($m^3$/min) | Advance time (min) |
|---|---|---|---|---|
| T1 | 1120 | 0.050 | 0.3036 | 688 |
| T2 | 840 | 0.050 | 0.3036 | 531 |
| T3 | 840 | 0.0262 | 0.3036 | 531 |
| T4 | 1120 | 0.050 | 0.3036 | 635 |
| T5 | 1120 | 0.0262 | 0.3378 | 635 |
| T6 | 1120 | 0.0262 | 0.3378 | 615 |
| T7 | 840 | 0.0262 | 0.3546 | 457 |
| T8 | 840 | 0.0262 | 0.3504 | 476 |
| T9 | 1120 | 0.0262 | 0.3504 | 673 |
| T10 | 1120 | 0.0262 | 0.3504 | 667 |
| T11 | 1120 | 0.0262 | 0.3504 | 662 |
| T12 | 1120 | 0.0262 | 0.3216 | 483 |
| T13 | 840 | 0.0262 | 0.3216 | 316 |
| T14 | 1120 | 0.0262 | 0.3216 | 446 |
| T15 | 1120 | 0.0262 | 0.3216 | 448 |
| T16 | 1120 | 0.0262 | 0.3678 | 383 |
| T17 | 840 | 0.0262 | 0.3678 | 199 |
| T18 | 840 | 0.0262 | 0.3678 | 195 |
| T19 | 840 | 0.0262 | 0.3678 | 192 |
| T20 | 1120 | 0.0262 | 0.2382 | 616 |
| T21 | 1120 | 0.0262 | 0.2382 | 612 |
| T22 | 1120 | 0.0262 | 0.4122 | 440 |
| T23 | 1120 | 0.0262 | 0.4134 | 439 |
| T24 | 1120 | 0.0262 | 0.3462 | 455 |
| T25 | 840 | 0.0262 | 0.4272 | 312 |
| T26 | 1120 | 0.0262 | 0.3876 | 498 |
| T27 | 1120 | 0.0262 | 0.3876 | 481 |

# Table 6.2 Summary of data sets for field C

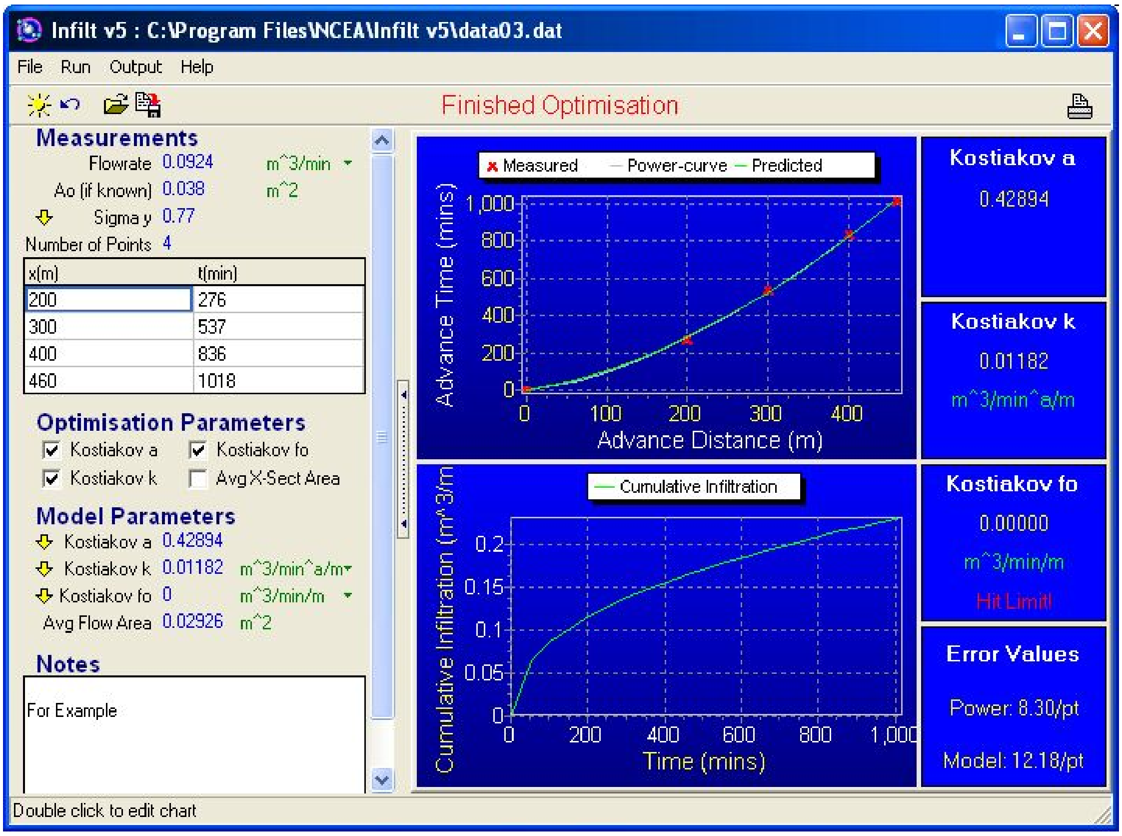
| Furrow | Length (m) | Cross-sectional area ($m^2$) | Flow rate ($m^3$/min) | Advance time (min) |
|---|---|---|---|---|
| C1 | 240 | 0.038 | 0.0498 | 273 |
| C2 | 240 | 0.038 | 0.0498 | 307 |
| C3 | 240 | 0.038 | 0.0498 | 336 |
| C4 | 240 | 0.038 | 0.0498 | 427 |
| C5 | 240 | 0.038 | 0.3126 | 277 |
| C6 | 240 | 0.038 | 0.3126 | 367 |
| C7 | 240 | 0.038 | 0.1566 | 238 |
| C8 | 240 | 0.038 | 0.1566 | 246 |
| C9 | 240 | 0.038 | 0.1566 | 210 |
| C10 | 180 | 0.038 | 0.2244 | 186 |
| C11 | 240 | 0.038 | 0.4752 | 109 |
| C12 | 240 | 0.038 | 0.1134 | 164 |
| C13 | 240 | 0.038 | 0.2286 | 126 |
| C14 | 180 | 0.038 | 0.27 | 144 |
| C15 | 240 | 0.038 | 0.27 | 189 |
| C16 | 180 | 0.038 | 0.27 | 124 |
| C17 | 240 | 0.038 | 0.27 | 171 |

### 6.3.2 INFILT Calculations

Infiltration parameters for each event of the fields were calculated from the full set of irrigation advance data using the INFILT program (McClymont and Smith, 1996) and are given in Appendix B (Table B.1 and B.2). INFILT is a computer software package (one of the IRRIMATE™ tools) designed to calculate soil infiltration parameters using only inflow and advance data. When the program is run the model shows initial program screen and then optimised infiltration parameter values and the cumulative infiltration and advance curves(Figure 6.1 a and b).




(a) INFILT program opening screen




(b) Example of INFILT screen showing optimised infiltration parameters

**Figure 6-1 INFILT screen shots**

The most common use of the program employs four or more advance points measured along the length of the furrow/field to determine best fit values for the three infiltration parameters *a, k* and $f_o$ of the Kostiakov-Lewis equation (and the average cross sectional area of the flow $\sigma_y A_o$ if this term is not known). However use of the cross-sectional area as an input parameter when it is known (or can be estimated) results in improved estimates of the infiltration parameters. INFILT was the preferred method for this study because of its proven performance over time and over a range of soils and situations (Khatri and Smith, 2005). Although INFILT only provides an estimate of the infiltration parameters or infiltration function, these estimates will be hereafter termed the actual infiltration or actual parameters to distinguish them from the scaled infiltration.

Spreadsheet programs (printouts given in Appendix B) were developed to plot the cumulative infiltration curves for each irrigation event using the above actual infiltration parameters ($a$, $k$ and $f_o$) in the Kostiakov–Lewis model.

### 6.3.3 REIP Calculations

This proposed method REIP uses the model curve concept to reduce the amount of data required for the estimation of the infiltration characteristics for each furrow and each irrigation event. Once the infiltration parameters of the model curve are known, this method requires inflow, cross-sectional area and only one advance point for each other furrow or event (measured mid-way down the furrow).

To test the proposed scaling method, it was applied to predict the infiltration characteristics for each event for the two fields T and C. Events T11 and C5 were selected as the model furrows for the two fields. The scaled infiltration parameters are given in Appendix B (Table B.3 and B.4).

A spreadsheet program was developed to calculate the scaling factor ($F$) for each other furrow from equation (6.2), using the infiltration parameters of the selected model curve and the single advance point. The scaling factors for both fields are given in Appendix B (Table B.3 and B.4). Equation (6.3) was then used to calculate the scaled cumulative infiltration curves for each irrigation event.

### 6.3.4 Prediction of advance curves

To evaluate the accuracy of infiltration estimates given by the scaling method and the ability of the method to reproduce the irrigation advance (particularly the total advance time), the advance curves were predicted for each event using the scaled infiltration parameters in the volume balance model:

$$Q_o t = \sigma_y A_o x + \sigma_z k t^a x + \frac{f_o t x}{1+r} \tag{6.4}$$

Re-arranging gives:

$$x = \frac{Q_o t}{\sigma_y A_o + \sigma_z k t^a + (f_o t/(1+r))} \tag{6.5}$$

where: $x$ is the predicted advance distance (m) corresponding to time $t$ (min),

$\sigma_z$ is the sub-surface shape factor for the model furrow,

$a$, $k$, and $f_o$ are the infiltration parameters of the model curve,

$r$ is the power curve exponent for the model furrow,

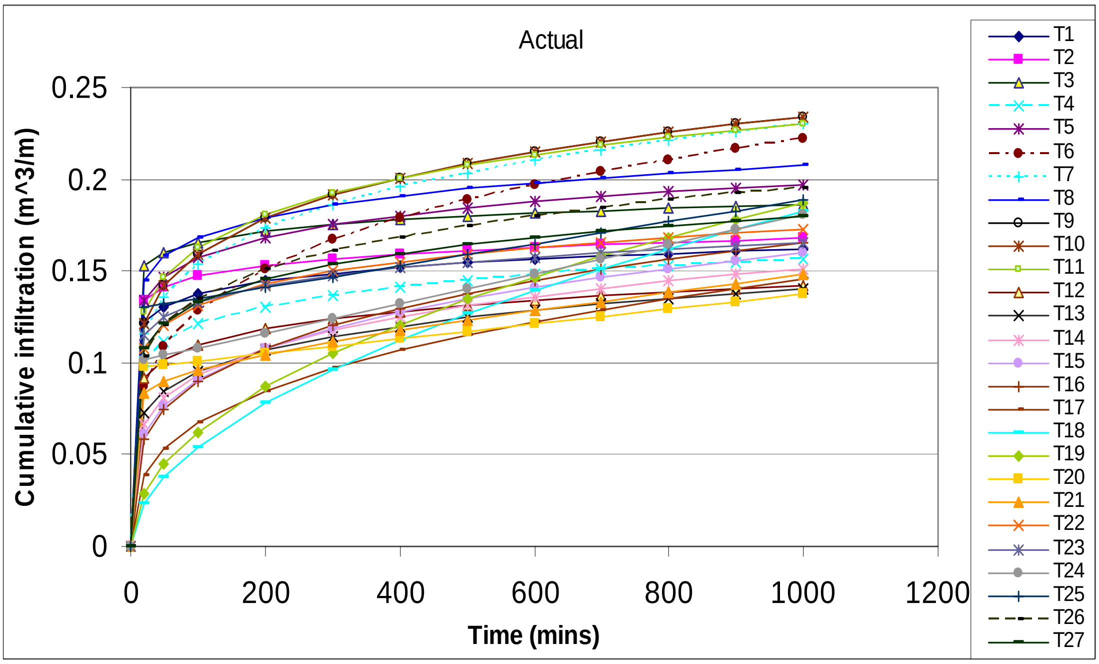
$Q_o$ and $A_o$ are the flow rate ($m^3$/min) and cross-sectional area of the target furrow ($m^2$), respectively.

## 6.4. Discussion on Results of Evaluation

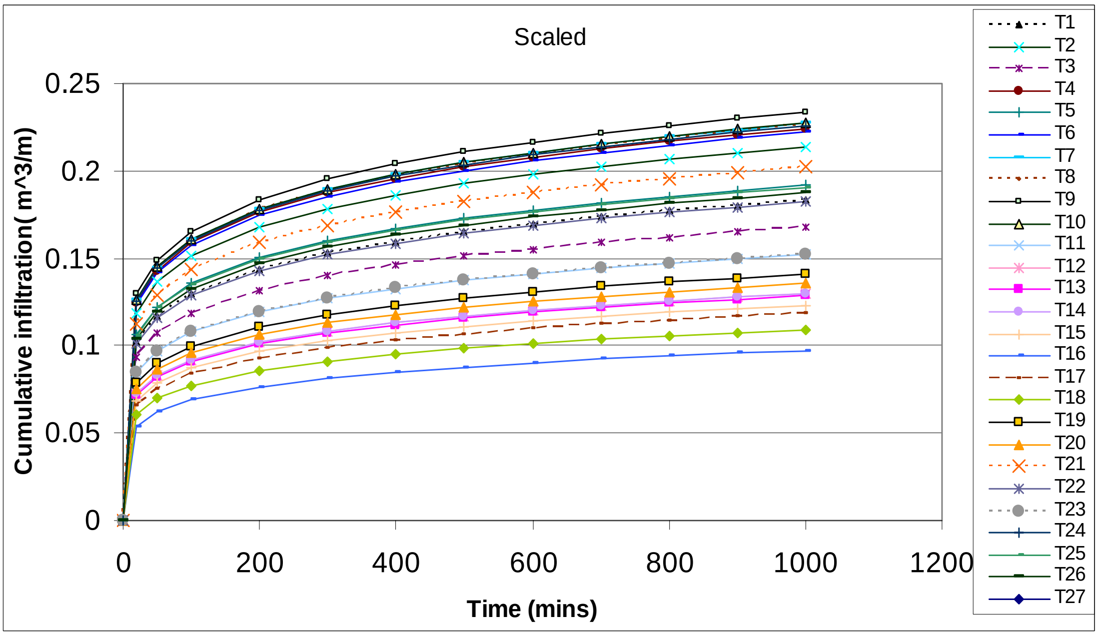
### 6.4.1 Comparison of infiltration curves

The actual cumulative infiltration curves for fields T and C are presented in Figures 6.2a and 6.3a, respectively. In the case of field T (Figure 6.2a) all curves are similar in shape, typical of that for a cracking clay soil and returned low $a$ values and $f_o$ of zero. The differences between the curves can be attributed to changes in pre-irrigation soil moisture content and the degree of cracking. In the case of field C, Figure (6.3a) clearly shows that this field has a large variability in infiltration both spatially and temporally. The cumulative infiltration curves have very different shapes most probably reflecting a change in soil characteristics or soil types across this field (but the data on soil types was not available from the original study that gathered the data).

The scaled cumulative infiltration curves for the two fields are presented in Figures 6.2b and 6.3b, respectively. From these figures it can be seen that the shapes of the scaled and actual infiltration curves (obtained by INFILT applied to a full set of data) are similar although some differences are evident as shown in figure 6.2 (a and b) for field T. However they give similar estimates of the cumulative infiltration at various times up to the advance time for each trial.

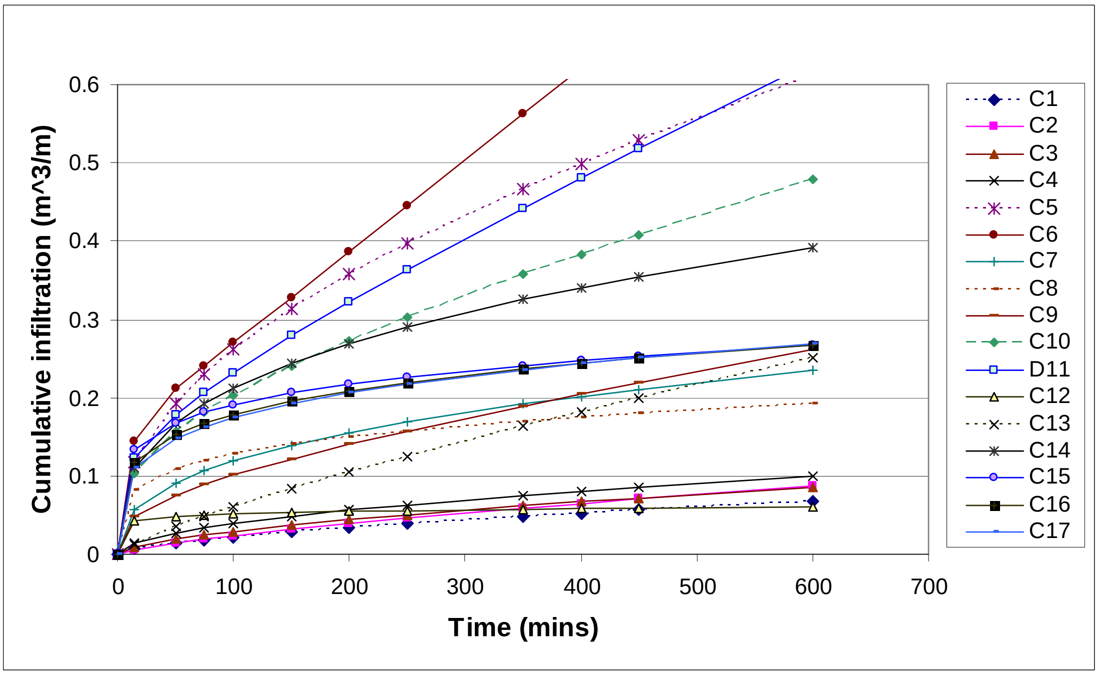



(a) Actual infiltration curves from INFILT infiltration parameters

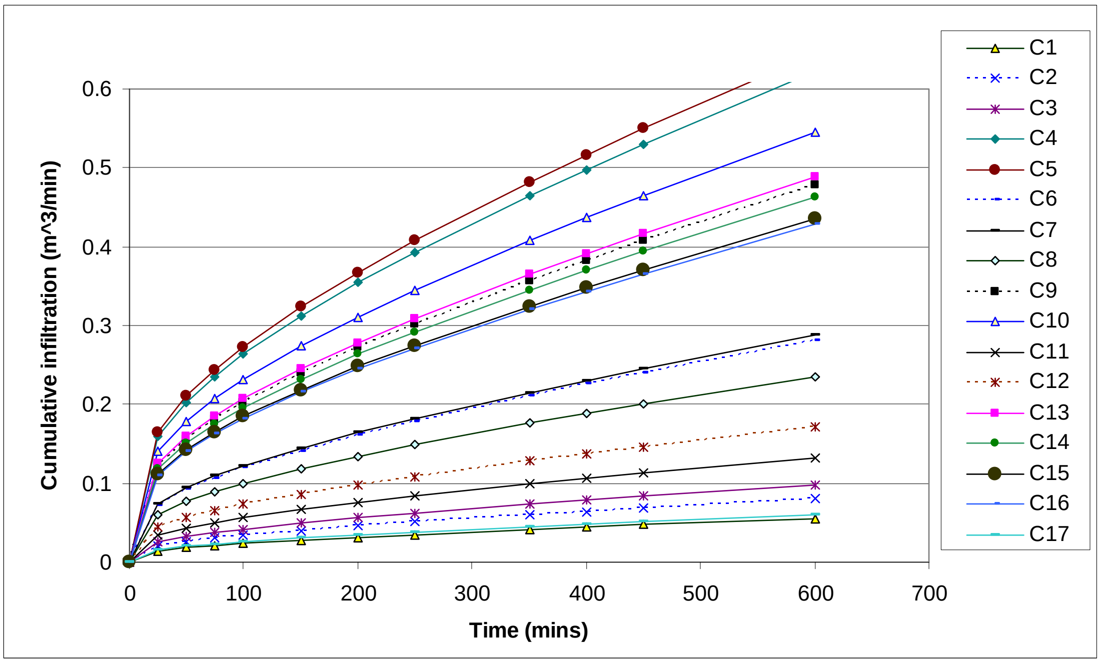



(b) Scaled infiltration curves

**Figure 6-2 Cumulative infiltration curves for field T**



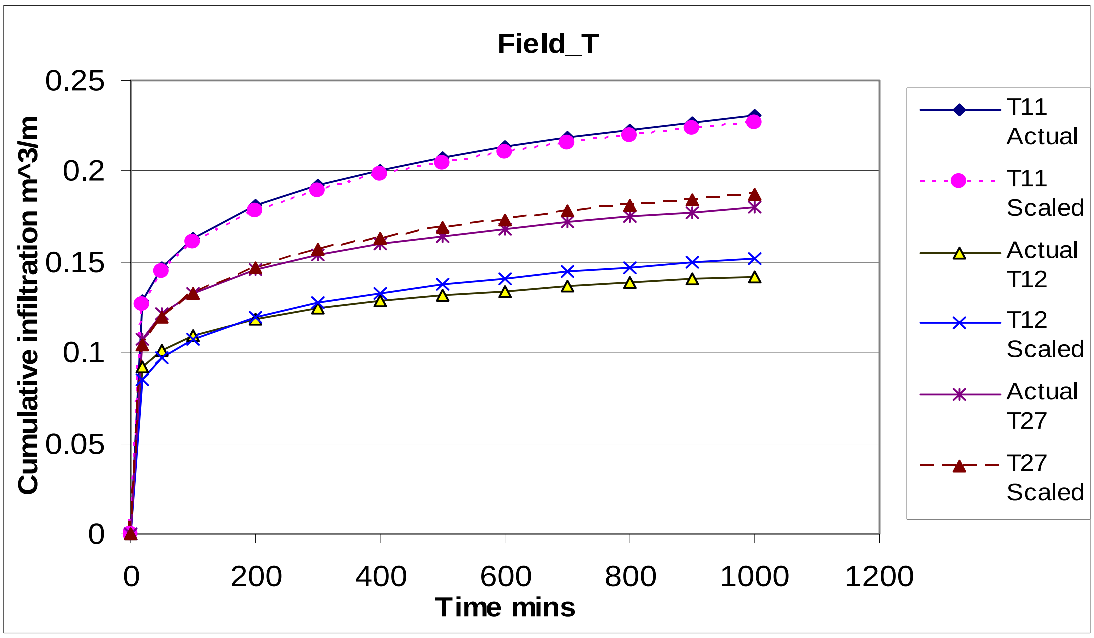

(a) Actual infiltration curves from INFILT infiltration parameters



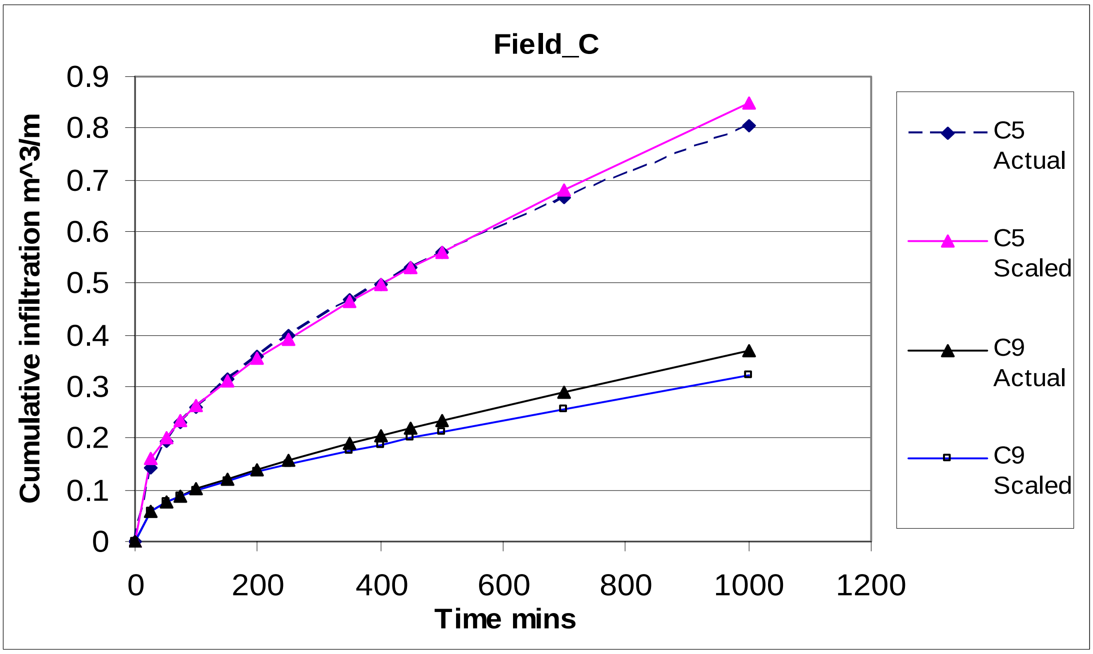

(b) Scaled infiltration curves

**Figure 6-3 Cumulative infiltration curves for field C**

To further illustrate the similarity between the scaled and actual infiltration, the scaled and actual cumulative infiltration curves for each furrow were compared individually. For example, in the case of field T, the actual cumulative infiltration curves and the scaled cumulative infiltration curves for the data sets (T11, T12 and T27) give almost identical predictions of the cumulative infiltration up to the advance times (662, 483 and 481 min, respectively) but diverge slightly beyond these times as shown in Figure 6.4(a). The comparisons were similarly good for most furrows at this site. Similarly in case of field C, the actual and scaled cumulative infiltration curves for the data sets C10 and C9 show almost exactly similar predictions for the cumulative infiltration depth (closest to actual) up to the lower advance times (about 250 mins) as shown in figure 6.4(b).




(a) Field T




(b) Field C

**Figure 6-4 Comparison of scaled and actual cumulative infiltration curves for individual furrows**

***Statistical analysis***

While the above comparisons show that the scaling gives acceptable reproduction of the infiltration curves for most furrows, this is not necessarily the intent of the method. The scaling will be successful (for the purpose of inclusion in a real-time control system) if the mean and variability of the cumulative infiltration over the field and/or over time is predicted successfully. This implies that the irrigation performance for that field will also be predicted successfully, the confirmation of which is given in the chapter 7 of this dissertation.

To assess this global correlation between the actual and scaled infiltration curves, the cumulative infiltration depths obtained at different times up to the advance time were analysed statistically.

Figure 6.5 shows the actual cumulative infiltration at a particular time (200 min) for each of the 27 irrigation events at field T plotted against the scaled cumulative infiltration for the same events. The linear trend line produced is very close to the 1:1 line giving the regression equation $I_{scaled} = 1.0149 I_{actual}$ and coefficient of determination $R^2 = 0.9259$. A T-test analysis for this same group of cumulative infiltration depths revealed that the means of actual and scaled infiltration depths at 200 min are not significantly different ($P \leq 0.05$).

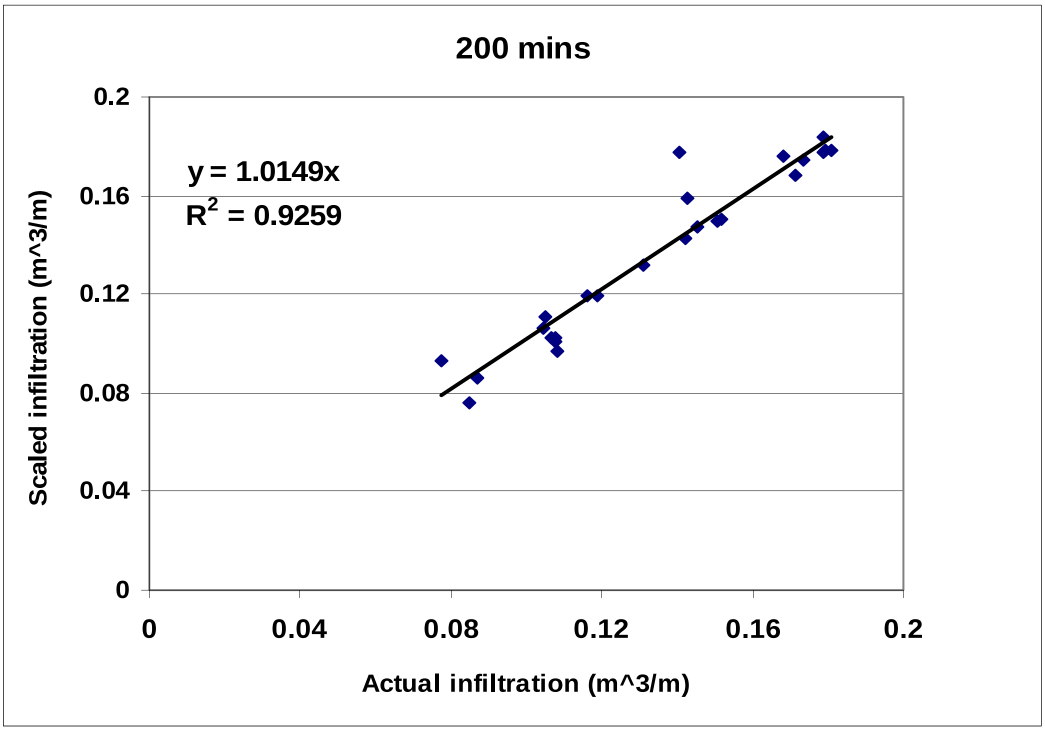



**Figure 6-5 Scaled cumulative infiltration vs actual cumulative infiltration (at 200 min) for the 27 irrigation events at field T**

The means of the scaled cumulative infiltrations at various times up to the advance time for the 27 irrigation events (Table 6.3) were also found to be very close to those for the actual curves, as shown below in Figure 6.6. The Pearson correlation for the means was 0.99.

Similarly the variances (expressed as coefficients of variation) of the scaled and actual cumulative infiltration depths at these same times compare favourably. For the scaled infiltration the CV is a constant 0.26 while for the actual infiltration the CV varies from 0.32 at 50 min down to 0.18 at 700 min. The cause for this difference is found in the three infiltration curves for furrows T17, T18 and T19 (Figure 6.2a). The irrigation advance for each of these furrows was very fast (< 200 min), indicating a relatively low infiltration rate for these furrows. However the final infiltration rate, calculated for these furrows using INFILT appears excessive for the field and produces a different shaped infiltration curve to the remaining curves for the field. While giving low infiltration at the early times these three curves must be considered unreliable when extrapolated to times greater than the advance times. The CV of the actual curves at 200 min is 0.25.

**Table 6.3 Mean of the actual and the scaled infiltration depths at various times up to advance time for field T.**

| Time (min) | Actual mean infiltrated depth at various times ($m^3/m$) | Scaled mean infiltrated depth at various times ($m^3/m$) |
|---|---|---|
| 0 | 0 | 0 |
| 50 | 0.109 (0.317) | 0.111 (0.258) |
| 100 | 0.120 (0.281) | 0.123 (0.258) |
| 200 | 0.134 (0.246) | 0.136 (0.258) |
| 300 | 0.144.(0.225) | 0.145 (0.258) |
| 400 | 0.152.(0.210) | 0.151 (0.258) |
| 500 | 0.158 (0.199) | 0.156 (0.258) |
| 600 | 0.164 (0.190) | 0.161 (0.258) |
| 700 | 0.169 (0.184) | 0.165 (0.258) |

(CV, Coefficient of variation in brackets)

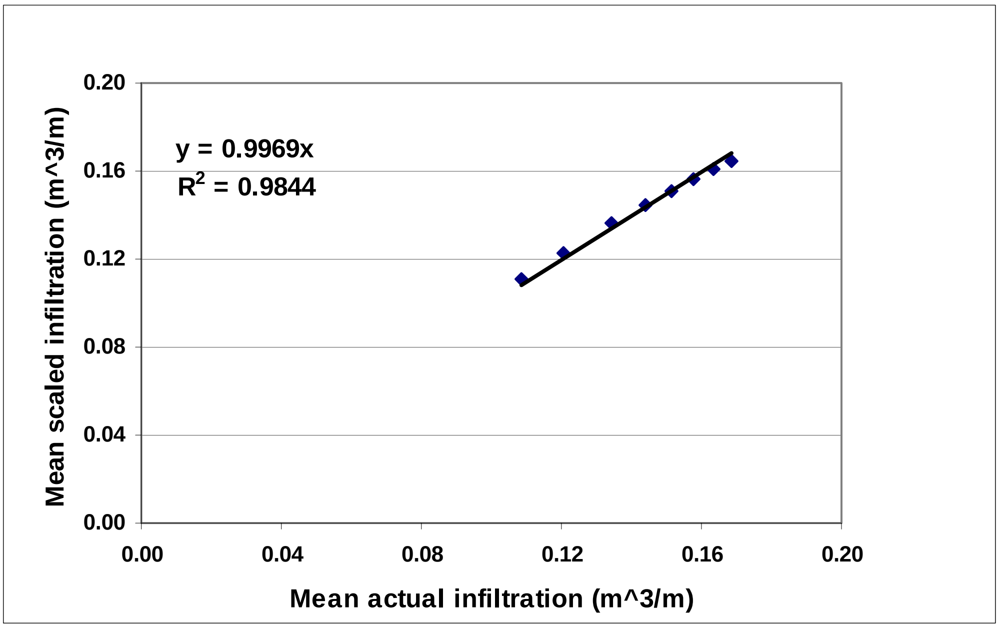



**Figure 6-6 Mean of the scaled cumulative infiltrations vs the mean of actual cumulative infiltrations at various times for the 27 irrigation events at field T**

The strong correlations between the scaled and actual infiltration clearly demonstrate suitability of the scaling process for predicting the infiltration characteristics while using only a minimum of field data. Chapter 5 has shown that previous methods based solely on one advance point are unreliable when applied across different soil types. This is because by use of particular infiltration equation they constrain the solution to particular soil types. By using the model infiltration curve, which is specific to the field in question, in conjunction with the single advance point, the above results indicate that greater accuracy and reliability can be obtained.

## 6.4.2 Comparison of advance curves

The predicted and measured advance curves for field T are presented in Appendix B (Figure B.1). From these curves it can be seen that the proposed method has predicted advance trajectories of similar form to the measured advance, with only minor differences in the final advance distances and at early times.

This is to be expected because the method guarantees that the advance trajectory will pass through the selected mid-point, as shown in Figure 6.7 given below for data sets T11, T12 and T22. A more complete evaluation of the ability to reproduce advance curves from the scaled infiltration, using the simulation model SIRMOD, has been given in chapter 7 on simulation and modelling of irrigation performance.

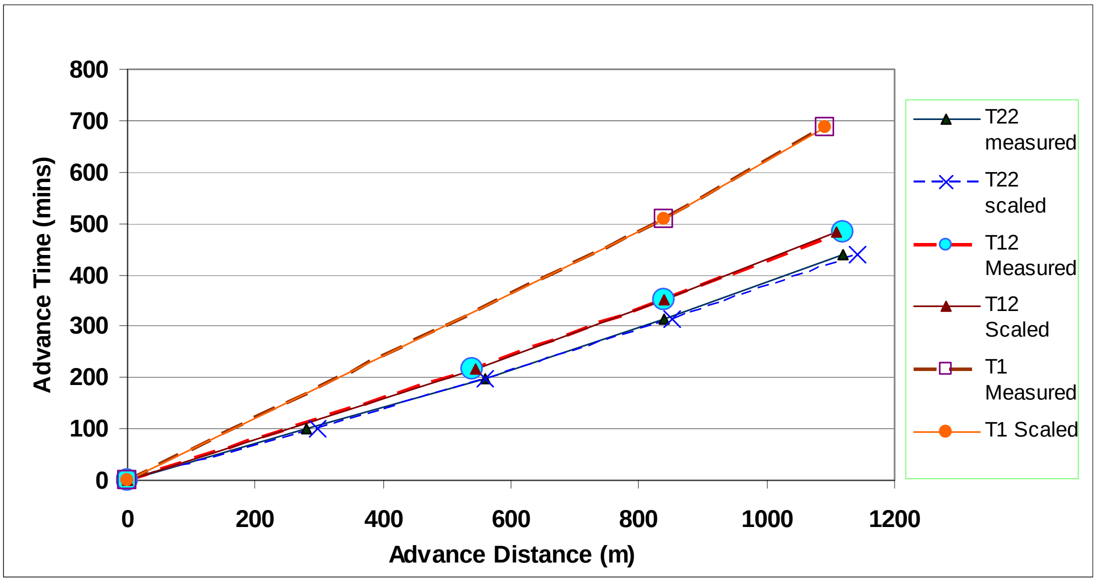



**Figure 6-7 Comparison of individual advance trajectories for field T**

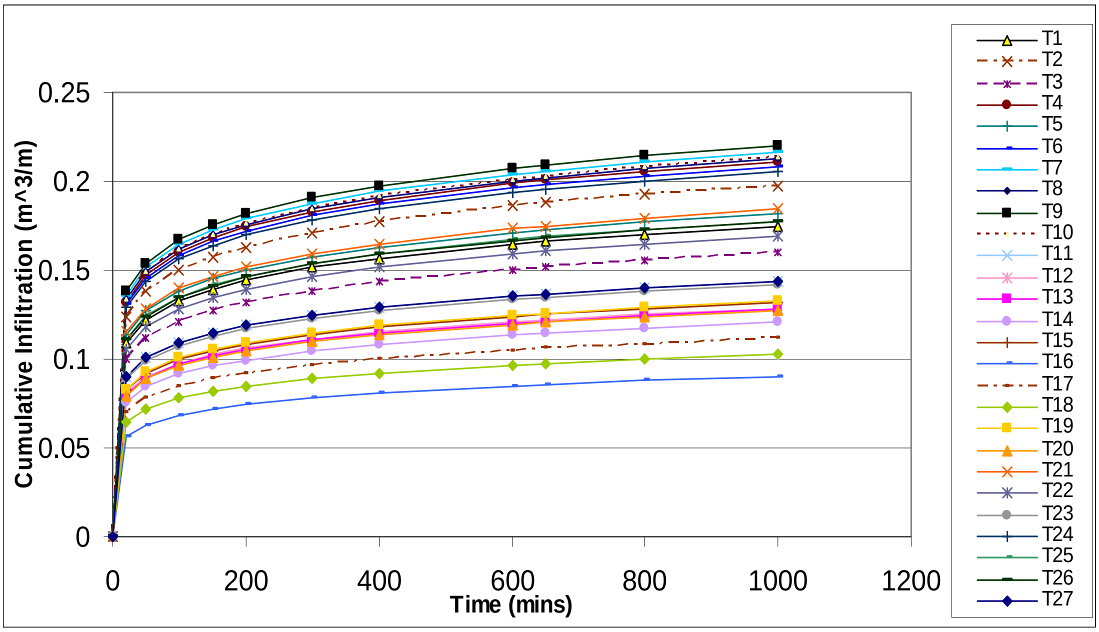
## 6.4.3 Discussion on REIP method

***Varying the model curve***

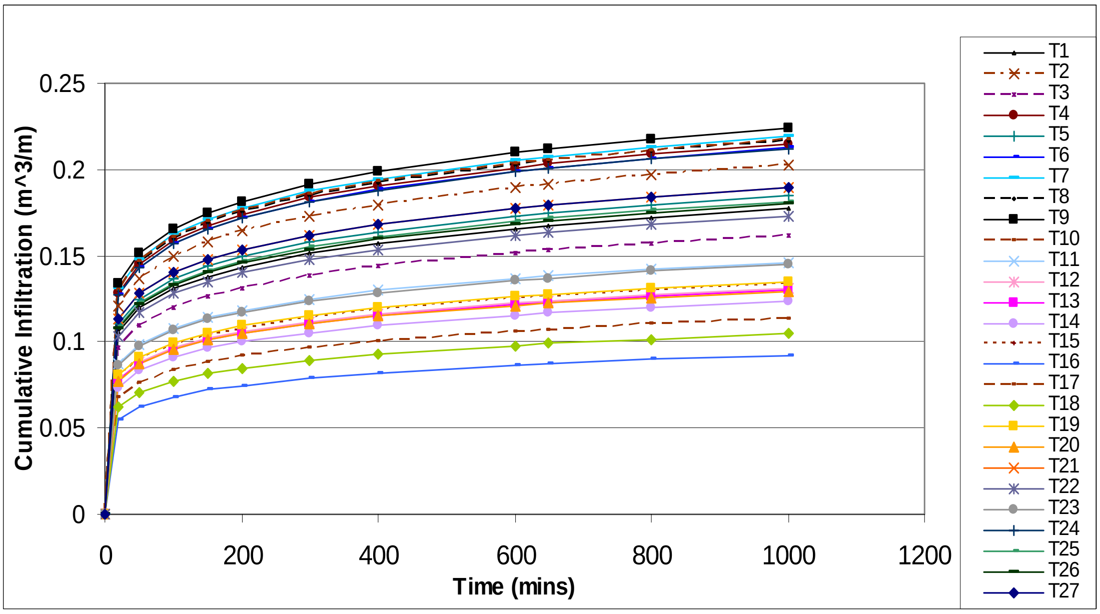
To determine the impact, if any, of selecting a different model curve (equivalent to selecting a different furrow for evaluation in the field), the method was tested using different model curves for both fields, showing low, medium and high infiltration. For instance in the case of field T, T22 and T27 were selected as the model curves and the scaled cumulative infiltration curves (obtained using these two different model curves) are shown in Figure 6.8. Likewise for field C, C5 and C9 were selected as the model curves and the cumulative infiltration curves scaled for this field (using the above two model curves) are shown in Figure 6.9.

From Figures 6.8 and 6.9, it is evident that selection of a different model curve does not have any significant impact on the scaled infiltration curves obtained for the both fields. Despite using different model curves they give almost identical estimates of the cumulative infiltration depth at various times up to the advance time (600 and 250 min for fields T and C, respectively). This indicates that the method is not limited to a specific model curve and hence selection of the furrow for full field evaluation is not critical to the process.

However as the model curve plays a highly significant role in the proposed method, it is important that the infiltration parameters of the model curve should be calculated as accurately as possible. This suggests the use of more rather than less data for evaluation of the model furrow including the use of run-off data in addition to advance data (Gillies and Smith, 2005).

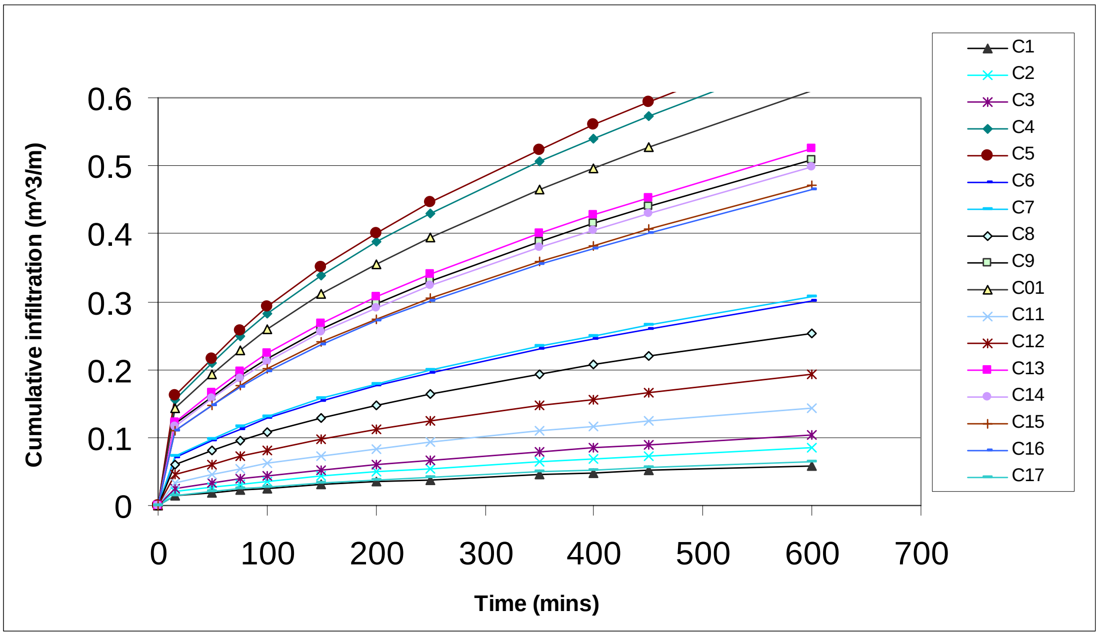



(a) Using furrow T22

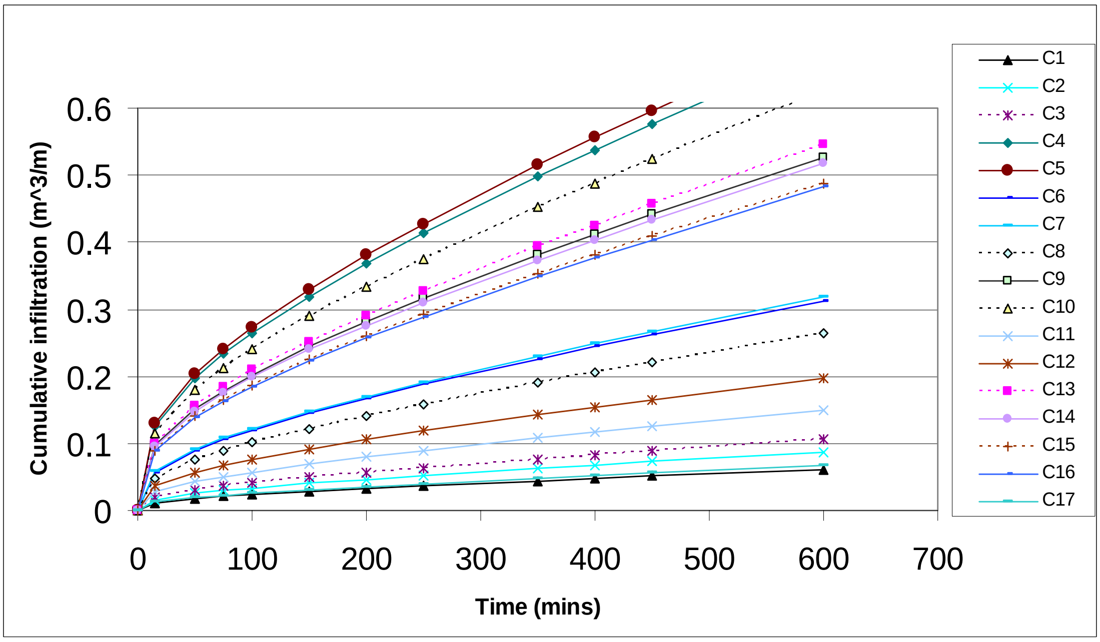



(b) Using furrow T27

**Figure 6-8 Effect of using a different model furrow for field T**




(a) Using furrow C10




(b) Using furrow C9

**Figure 6-9 Effect of using a different model furrow for field C**

***Consistency of p and r values***

The volume balance equation (6.2) and the INFILT computer program assume that the irrigation advance follows the power curve equation:

$$x = p(t)^r \tag{6.6}$$

where $t$ is the time taken for the wetting front to reach advance distance $x$, and $p$ and $r$ are fitted parameters. Further, the scaling method evaluated in this paper assumes that the exponent $r$ is constant for a particular field.

Table 6.4, shows the values of $p$ and $r$ taken from the INFILT calculations for each irrigation event from the two fields. From Table B.8 it is quite evident that the p values involve large variations, from 2.34 to 15.87. The table further shows that the $r$ values exhibit a relatively small variation, ranging between 0.73 and 0.97 for field T, and between 0.62 and 0.85 for field C, indicating the consistency of this parameter for a whole field. Given that the scaling factor appears relatively insensitive to small changes in this parameter (see equation 6.2), hence using a constant value of $r$ for a field is not unreasonable. As well as since the scaling procedure assumes a unique value of the exponent $a$ in the infiltration equation, it should follow that the advance exponent should be same as well. The data in Table B.8 also indicate that for a particular field the difference between the measured advance curves for the various events is described almost entirely by the coefficient $p$.

**Table 6.4 Power curve *p* & *r* values for fields T and C**

| Field T | *r* | *p* | Field C | *r* | *p* |
|---|---|---|---|---|---|
| T1 | 0.856 | 4.115 | C1 | 0.714 | 4.288 |
| T2 | 0.939 | 2.311 | C2 | 0.679 | 4.892 |
| T3 | 0.939 | 2.311 | C3 | 0.639 | 5.609 |
| T4 | 0.898 | 3.363 | C4 | 0.684 | 3.772 |
| T5 | 0.898 | 3.363 | C5 | 0.617 | 7.500 |
| T6 | 0.791 | 7.019 | C6 | 0.686 | 7.763 |
| T7 | 0.833 | 5.094 | C7 | 0.694 | 5.284 |
| T8 | 0.911 | 3.044 | C8 | 0.808 | 2.806 |
| T9 | 0.826 | 5.116 | C9 | 0.693 | 5.918 |
| T10 | 0.855 | 4.184 | C10 | 0.678 | 5.199 |
| T11 | 0.850 | 4.398 | C11 | 0.730 | 7.853 |
| T12 | 0.887 | 4.640 | C12 | 0.832 | 1.961 |
| T13 | 0.853 | 6.222 | C13 | 0.643 | 14.990 |
| T14 | 0.816 | 7.709 | C14 | 0.703 | 5.385 |
| T15 | 0.799 | 8.549 | C15 | 0.850 | 2.786 |
| T16 | 0.777 | 11.073 | C16 | 0.808 | 4.651 |
| T17 | 0.751 | 15.875 | C17 | 0.800 | 3.901 |
| T18 | 0.765 | 14.910 | | | |
| T19 | 0.729 | 13.603 | | | |
| T20 | 0.927 | 2.906 | | | |
| T21 | 0.879 | 3.962 | | | |
| T22 | 0.884 | 5.178 | | | |
| T23 | 0.904 | 4.598 | | | |
| T24 | 0.905 | 4.436 | | | |
| T25 | 0.971 | 3.214 | | | |
| T26 | 0.841 | 6.035 | | | |
| T27 | 0.815 | 7.257 | | | |

***Selection of advance point***

Advance points around the mid point of the furrow length were selected for the purpose of real-time control as mentioned earlier in this chapter. The mid point was preferred so as to allow time for the data acquisition, simulation, optimisation and control of the irrigations. In the case of some furrows, where the true mid point was not available, an alternative advance point nearest to the mid point was used. As reported in this Chapter, use of the mid point has shown satisfactory results for estimation of the infiltration parameters and offers potential for real-time control of furrow irrigated soils. However there is no strong evidence that the mid point is the best point.

To determine how the scaling factor *F* might vary with selection of the advance point, scaling factors were calculated for field C at different advance points along the length of the furrows at 25, 50, 75 and 100% of the distance from the furrow head. The results of these calculations are presented in Table 6.4. The correlations between the scaling factor values are shown in Figure 6.10.

The results show that the scaling factor varies along the length of furrow in a slightly inconsistent manner. There is no difference between scaling factor values obtained at the 25 and 50% points of the furrows. For most furrows the scaling factor values increased with increasing distance beyond 50%. In some cases differences up to 27% were observed between the values calculated at the mid and end points. In a small number of furrows the scaling factors decreased with distance. However, the differences between the mid point and end point scaling factor values are not statistically significant.

The cause of these differences in the scaling factor is not known. Variation of the scaling factor with distance might be caused by the shape of the advance curve or it might be an artefact of inaccuracies in the estimates of the actual infiltration from the

INFILT program. Further work with a greater range of advance data would be needed to clarify this issue.

## Table 6.5 Scaling factor *(F)* values calculated along length of furrow for field C.

| *Events* | *F* | *F* | *F* | *F* |
|---|---|---|---|---|
| | *0.25L* | *0.5L* | *0.75L* | *L* |
| C1 | 0.261 | 0.266 | 0.257 | 0.282 |
| C2 | 0.264 | 0.260 | 0.276 | 0.308 |
| C3 | 0.254 | 0.274 | 0.309 | 0.352 |
| C4 | 0.361 | 0.365 | 0.380 | 0.416 |
| C5 | 0.687 | 0.686 | 0.726 | 0.741 |
| C6 | 0.704 | 0.714 | 0.721 | 0.738 |
| C7 | 0.489 | 0.487 | 0.623 | 0.657 |
| C8 | 1.044 | 1.042 | 1.239 | 1.313 |
| C9 | 0.944 | 0.947 | 1.048 | 1.101 |
| C10 | 0.421 | 0.413 | 0.387 | 0.369 |
| C11 | 0.563 | 0.571 | 0.619 | 0.646 |
| C12 | 1.083 | 1.088 | 1.174 | 1.230 |
| C13 | 1.112 | 1.100 | 1.074 | 1.054 |
| C14 | 0.993 | 0.990 | 0.996 | 0.998 |
| C15 | 0.957 | 0.952 | 0.965 | 0.968 |
| C16 | 0.993 | 0.990 | 0.996 | 0.998 |
| C17 | 0.957 | 0.952 | 0.965 | 0.968 |

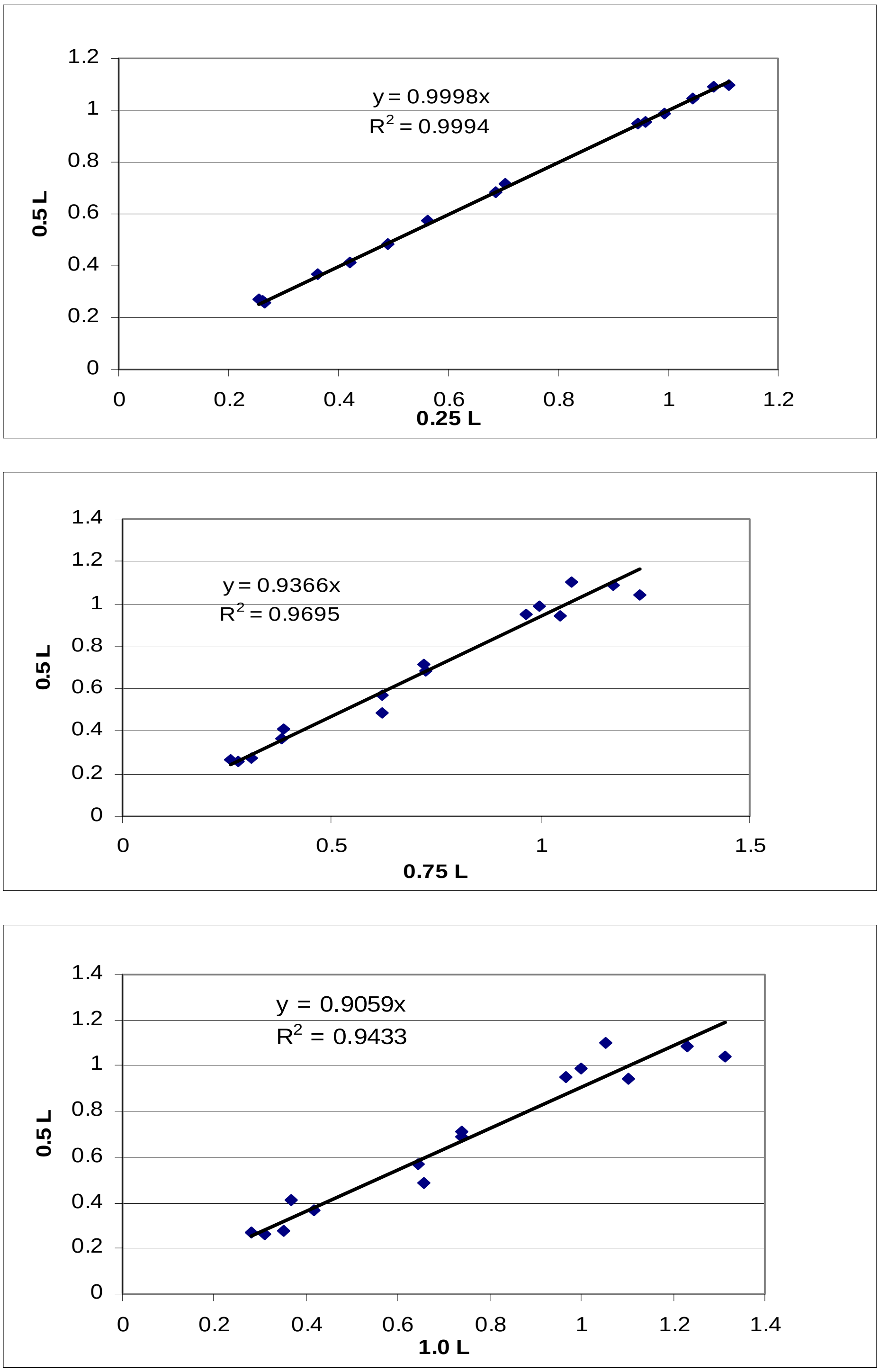



**Figure 6-10 Relationship between scaling factor values at different advance points for field C**

## 6.5. Conclusions

A method of scaling has been proposed for the estimation of soil infiltration parameters in real-time from a minimum of furrow irrigation advance data. It employs a model infiltration curve for the field and predicts the infiltration for each furrow using only one advance point measured mid-way down the furrow.

The proposed method was evaluated using data from 44 irrigation events on two fields having different infiltration characteristics and for which extensive advance data were available. The data for each field encompassed multiple furrows and multiple irrigations and define the extent of the spatial and temporal variability in the infiltration at each site.

The results from the evaluation indicated that:

- the scaled infiltration curves were of similar shape to the actual curves and gave nearly identical depths of infiltration up to the advance time for each furrow,
- the mean and variance of the scaled and actual infiltration at various times were similar, and
- the method was not sensitive to the choice of furrow used to give the model infiltration curve.

On the basis of these results it can be concluded that the proposed method has the potential for use in real-time control and management of furrow irrigation.

# Chapter 7

# Simulation and Modelling of Performance for a Simple Real-time Control of Furrow Irrigation

## 7.1 Introduction

Furrow irrigation system analysis is generally based on field data collected from a limited number of furrows (Elliot & Walker 1982; Renault & Wallender 1992; Shepard *et al*. 1993). This analysis is used to provide a recommended inlet discharge and cut-off time combination that will improve irrigation uniformity and efficiency. The analysis assumes infiltration properties are constant throughout the cropping season, although field studies have shown otherwise (Childs *et al*. 1993; Mailhol *et al.* 1999; Mailhol 2003). In addition to infiltration, field elevation, cross-sectional profile and roughness are inherent variables in furrow systems. All these factors produce variations in advance rates among furrows and non-uniform water distribution over an entire field.

Some studies have examined the impact of spatial variability of infiltration, at the furrow scale (Bautista & Wallender 1985; Wallender 1987; Bautista & Wallender 1992) and on field-wide irrigation efficiency (Schwankl *et al*. 2000). Lamacq and Wallender (1994) evaluated the impact of water delivery flexibility on furrow irrigation performance. The simulation model FHYDDT (Bautista & Wallender 1992) was used to calculate water application depth along the furrow. The calculated water application depth was used as an input for a soil water balance model

(SWSSM) that updated soil moisture as a function of potential evapotranspiration. The furrow model FHYDDT uses the extended Kostiakov infiltration equation. To address seasonal variation in infiltration characteristics, a set of extended Kostiakov parameters was used for pre-irrigation and a second set for the rest of the season. Simulations were performed on a single furrow but the resulting water distribution value was assumed to be applicable to the entire field. Thus the study ignored the differences in advance rates among furrows, which are commonly observed in the field. Such variations can have significant impacts on field-wide efficiency and uniformity.

Furrow irrigation usually delivers a constant discharge $Q$ into the furrows. Empirical rules are often used by growers to determine the time of cutoff ($t_{co}$) corresponding to the application rate. The selected management variables $Q$ and $t_{co}$ are usually not adequate. Determining optimum $Q$ and $t_{co}$ requires knowledge of soil infiltration properties and their changes over time and space (Mailhol *et al.*, 1999).

Many models have been developed recently to simulate furrow irrigation (Walker & Humpherys 1983; Singh & Ram 1983; Wallender 1987; Schmit & Seus 1992). Most are not predictive models because soil infiltration properties are not known before the start of irrigation. In addition, their main purpose concerns the front advance solution, which is highly dependent on soil-infiltration properties. Infiltration properties of furrows are too complex to be described by deterministic approaches (Wallender 1987; Trout 1990), for this reason, empirical approaches are commonly used. Empirical models (analytical or numerical) use parameters calibrated with data collected during irrigation and are effective for a posteriori simulation of furrow irrigation (Fang & Singh 1990; Elliott & Walker 1982). But the set of empirical parameters calibrated with data collected during irrigation are not suitable for predicting subsequent irrigations. This also applies for empirical parameters derived from infiltration measuring methods (Haverkamp *et al.*, 1988). The reason is that conditions change for subsequent irrigations (e.g., different initial soil moisture, new discharge, and time of cutoff). The infiltration characteristic of the soil is the most crucial factor affecting the performance of surface irrigation (Chapter 5) and variations in the infiltration characteristic are a major physical constraint to achieving higher irrigation application efficiencies. A posteriori evaluation methods are therefore not always effective in helping farmers optimise irrigation.

In this chapter a simple real-time control system for furrow irrigation is proposed that predicts the infiltration characteristic of the soil in real-time using data measured during an irrigation event, simulates the irrigation and determines the optimum time to cut-off for that irrigation. The basis of the system is a new method for estimating the soil infiltration characteristic under furrow irrigation, developed in chapter 6, that uses a model infiltration curve, and a scaling process to predict the infiltration characteristic for each furrow and each irrigation event. Using the new method, infiltration parameters were calculated for two different fields. The SIRMOD simulation model was then used to simulate irrigation performance under different model strategies which were framed to assess the feasibility of, and demonstrate the gains from, the real-time control strategy. The simulation results showed that the system is feasible. The scaled infiltration gave predictions of the irrigation performance comparable to the measured performance, clearly establishing the suitability of this method for use in real-time control. The results further indicated that under simple real-time control the irrigation performance for the two fields could be improved greatly with reductions in the total volume of water applied to the two fields of 20% and 60% respectively, indicating the scale of benefits that can be achieved in the irrigation sector by implementing simple real-time control.

The work reported in this chapter is published as Khatri and Smith (2006) and is directed at the development of a simple and practical real-time control system for surface irrigation. The feasibility of the proposed system is assessed through simulation of the irrigation performance, using the scaled infiltration parameters given by the proposed method REIP and those estimated from full advance data. The gains in irrigation performance possible from adoption of the real-time control strategy are demonstrated.

## 7.2. Description of the proposed real-time control system

The proposed real-time control system involves:

- measurement or estimation of the inflow to each furrow or group of furrows,
- measurement of the advance at one point approximately midway down the furrow,
- estimation of the infiltration characteristic for the furrow or group of furrows using the REIP scaling technique (Chapter 6),
- simulation of the irrigation and optimization to determine the time to cut off the inflow.

The actual measurement, simulation and control would preferably be automated but could be undertaken manually with very little capital investment on the part of the farmer.

A necessary precursor to application of the system is the determination of the shape of the infiltration characteristic (model infiltration curve) for the particular field or soil type. This is best done from a comprehensive evaluation of one or more furrows from the field, involving measurements of the inflow, advance and where possible runoff, with the infiltration curve determined using a model such as INFILT (McClymont & Smith, 1996) or IPARM (Gillies & Smith, 2005). The preferred (constant) furrow inflow rate is also determined at this stage although it may be altered over time as experience with operation of the system is accumulated.

## 7.3. Analysis

### 7.3.1 Irrigation performance and infiltration data

The irrigation advance data for the all irrigation events for field T and C used in Chapter 6 are used in this chapter to evaluate the real-time control.

The actual infiltration parameters and the scaled parameters for each furrow/event from the two fields, as calculated in chapter 6 by the INFILT software (McClymont & Smith, 1996) and the scaling method REIP, respectively, have been used here in simulation model strategies to assess the benefits from a simple real-time optimisation and control.

### 7.3.2 Simulation methodology

*SIRMOD (Surface Irrigation Simulation, Evaluation and Design)*

To test the proposed real-time control system, simulations were performed for the two fields using the actual (INFILT) and the scaled infiltration parameters in the simulation model SIRMOD (Walker, 2001). These SIRMOD simulations were used to compare the irrigation performance (application efficiency $E_a$, requirement or storage efficiency $E_s$, and distribution uniformity $E_d$) of the actual irrigations, recipe approaches to irrigation performance improvement, and the simple real-time control strategy.

SIRMOD is a software package designed to simulate the hydraulics of surface irrigation at the furrow scale, and to optimize the irrigation system parameters to maximize application efficiency. The input data required for the simulation component of the model include field length, slope, infiltration characteristics, target application depth, flow rate, Manning *n* and furrow geometry (Figure 7.1 to 7.4). The model output includes a detailed advance-recession trajectory, distribution of infiltrated water, volume balance, runoff hydrograph, water distribution uniformity, and the water application and requirement efficiencies (Figures 7.5 and 7.6). The ability of the SIRMOD to evaluate the irrigation performance of furrows and borders has been well documented (for example, McClymont *et al.*, 1996, Latif & Sajid 2004).

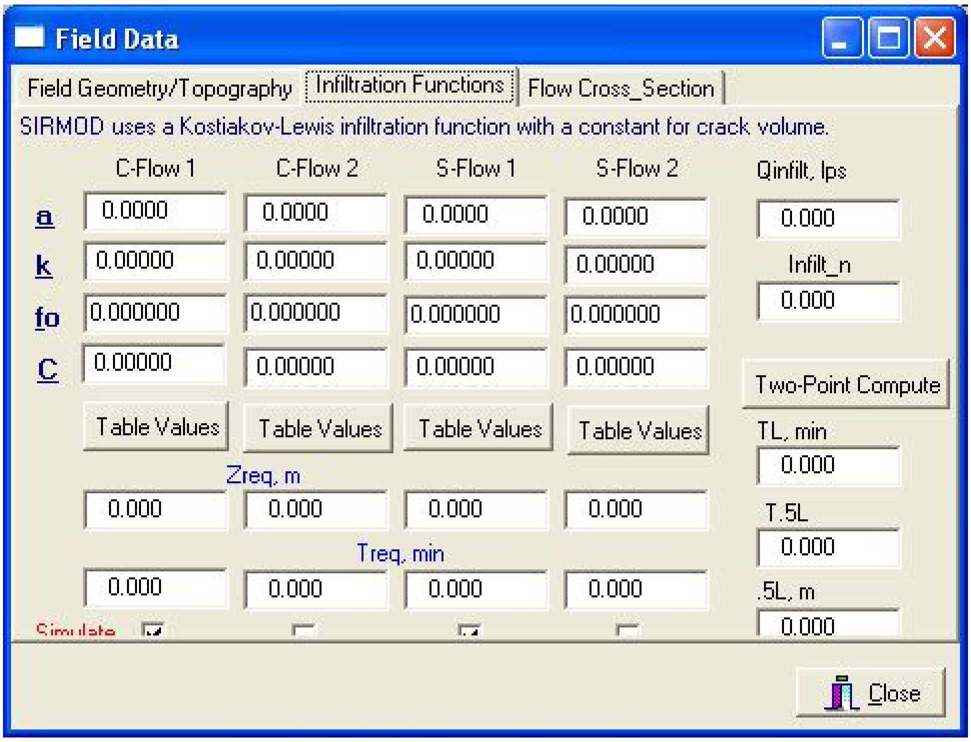



**Figure 7-1 Example of SIRMOD screen showing the data required for simulation under infiltration functions tab**

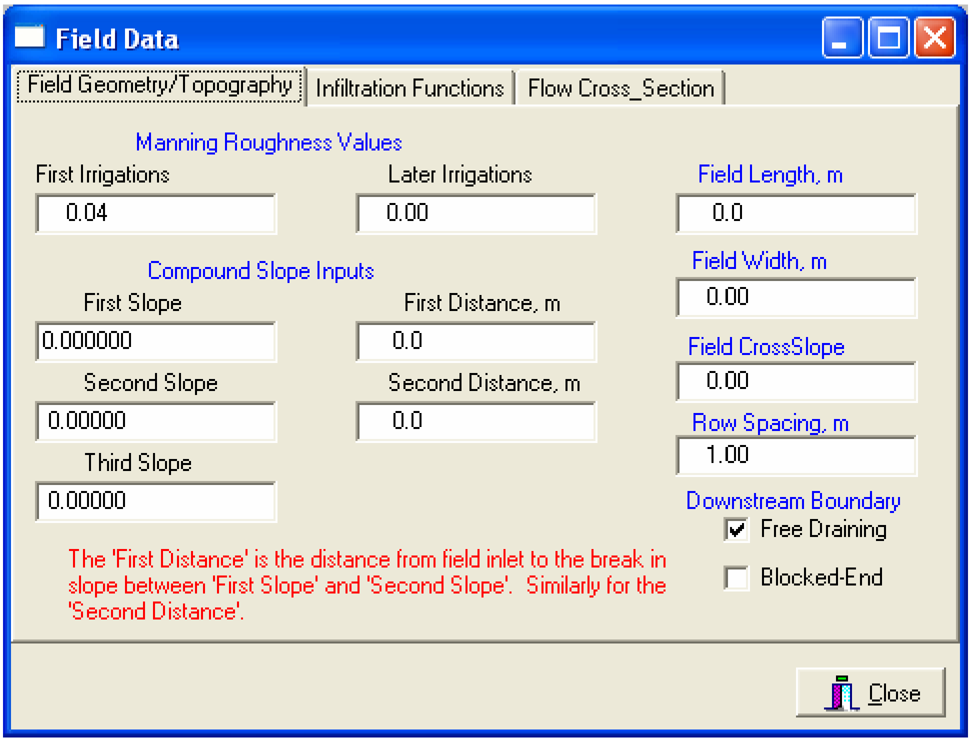



**Figure 7-2 SIRMOD screen showing the data required for simulation under field geometry tab**

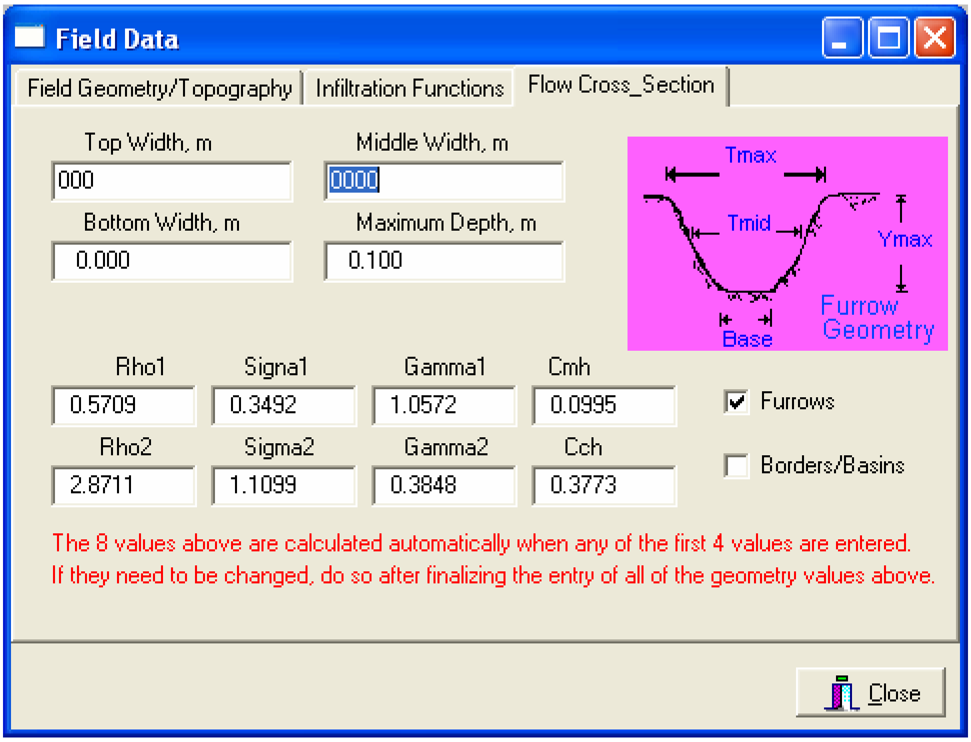



**Figure 7-3 SIRMOD screen showing the furrow geometry required for simulation under flow cross-section tab**

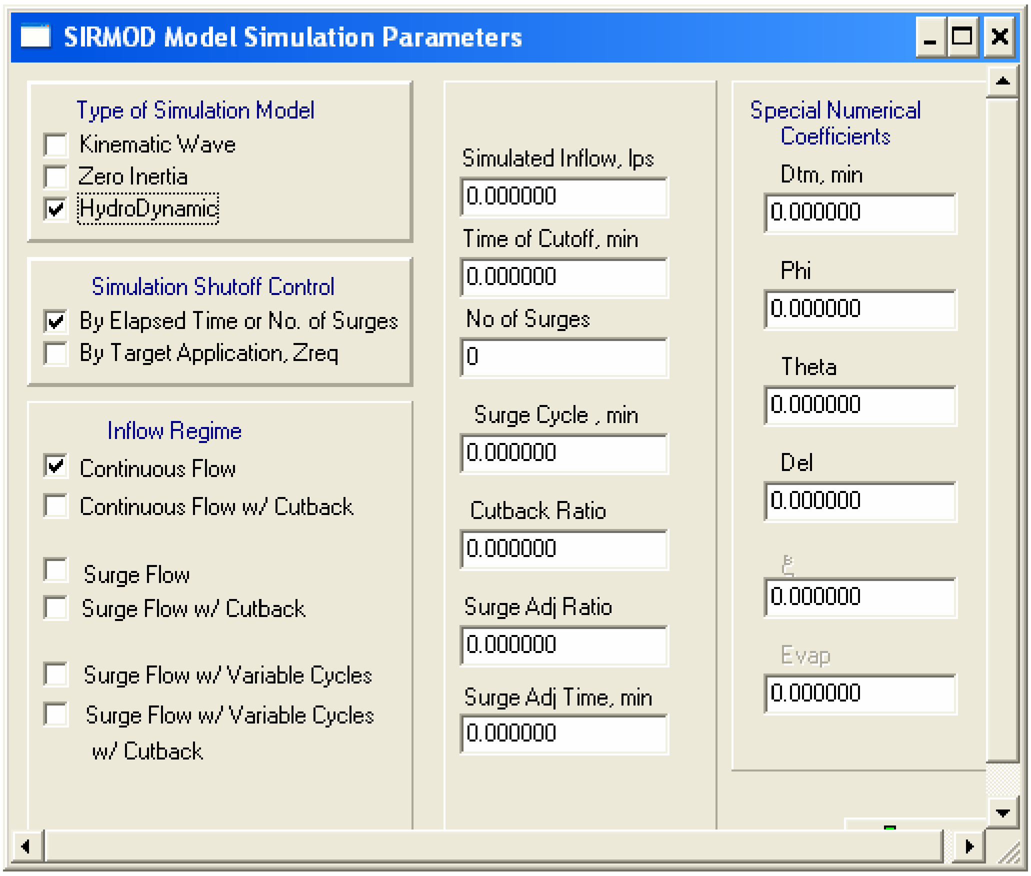



**Figure 7-4 SIRMOD screen showing the columns to be ticked during simulation operation.**

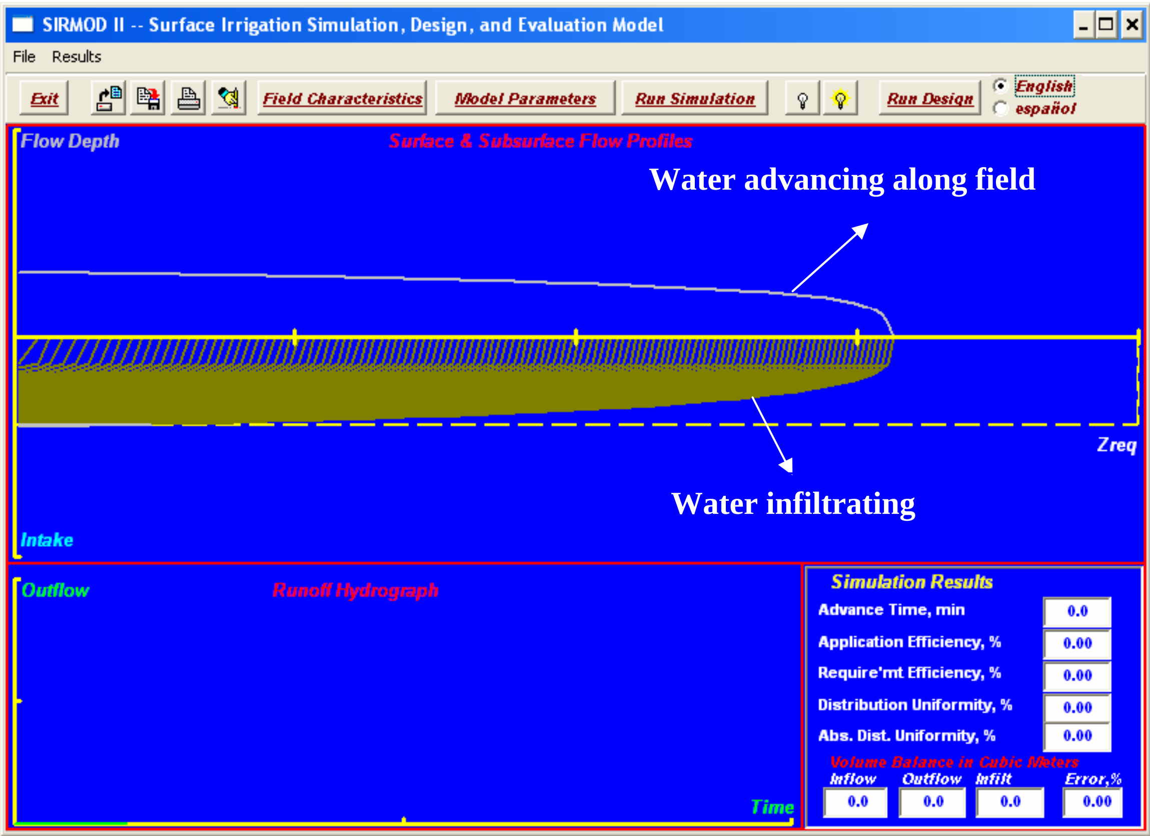



**Figure 7-5 SIRMOD screen showing the simulation process in operation.**

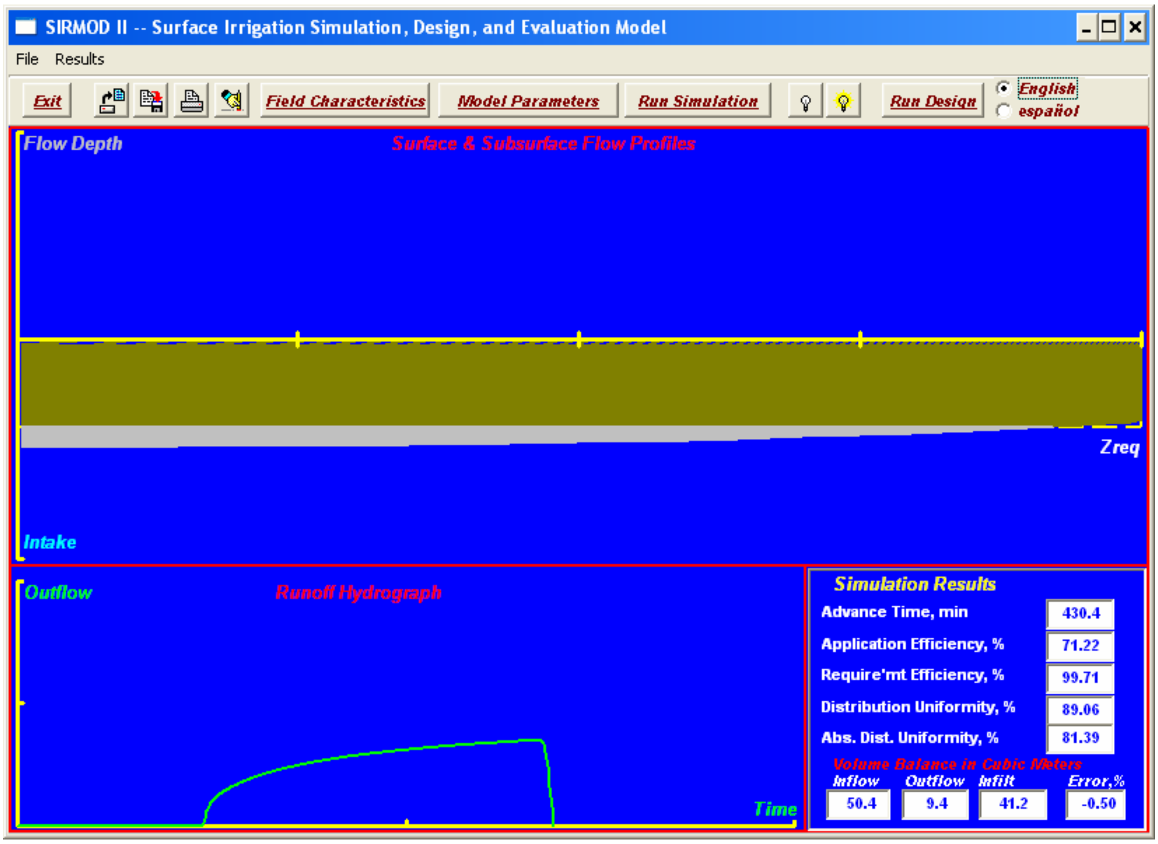



**Figure 7-6 SIRMOD screen showing the completed simulation process and run-off hydrograph.**

## 7.4 Simulation Model strategies

To perform the simulations, six (6) irrigation strategies were framed to test the proposed system and to demonstrate the achievable gains in irrigation performance. The model strategies adopted are:

Strategy 1: The actual irrigation simulated using the actual infiltration parameters (INFILT $a$, $k$, $f_o$), actual inflow ($Q_o$) and actual cut-off time ($t_{co}$) as recorded under usual farm practices.

Strategy 2: Prediction of the actual irrigation simulated using the scaled infiltration parameters, actual inflow and actual cut-off time.

Strategy 3: Optimisation of the actual irrigation. In this case, each irrigation event was optimised by using the INFILT parameters and varying the inflow and cut-off time to obtain maximum application efficiency ($E_a$). This strategy also indicates the best over all flow rate.

Strategy 4a: A simple recipe for performance improvement, simulated using the INFILT parameters and actual inflow but with the cut-off time fixed equal to 90% of the advance time.

Strategy 4b: An alternative recipe, simulated using the INFILT parameters, a fixed inflow as selected from strategy 3 and cut-off time equal to 90% of the advance time.

Strategy 5: A simple practical real-time control strategy in which the scaled infiltration parameters were used with a fixed inflow while varying/optimising only the cut-off time to achieve the best irrigation.

Strategy 6: Simulation of the actual result of the real-time control strategy (5), using the INFILT parameters and the same inflow and cut-off time as used in strategy 5.

## 7.5. Results and Discussion

### 7.5.1 Advance trajectories

The discussion in previous chapter on advance prediction that the scaled infiltration was able to reproduce the measured advance curves when applied in the same volume balance model that was used to generate the infiltration parameters. This ability is confirmed here by the SIRMOD simulations. The measured and simulated advance curves for field T are presented in Figures 7.6 and 7.7, respectively.

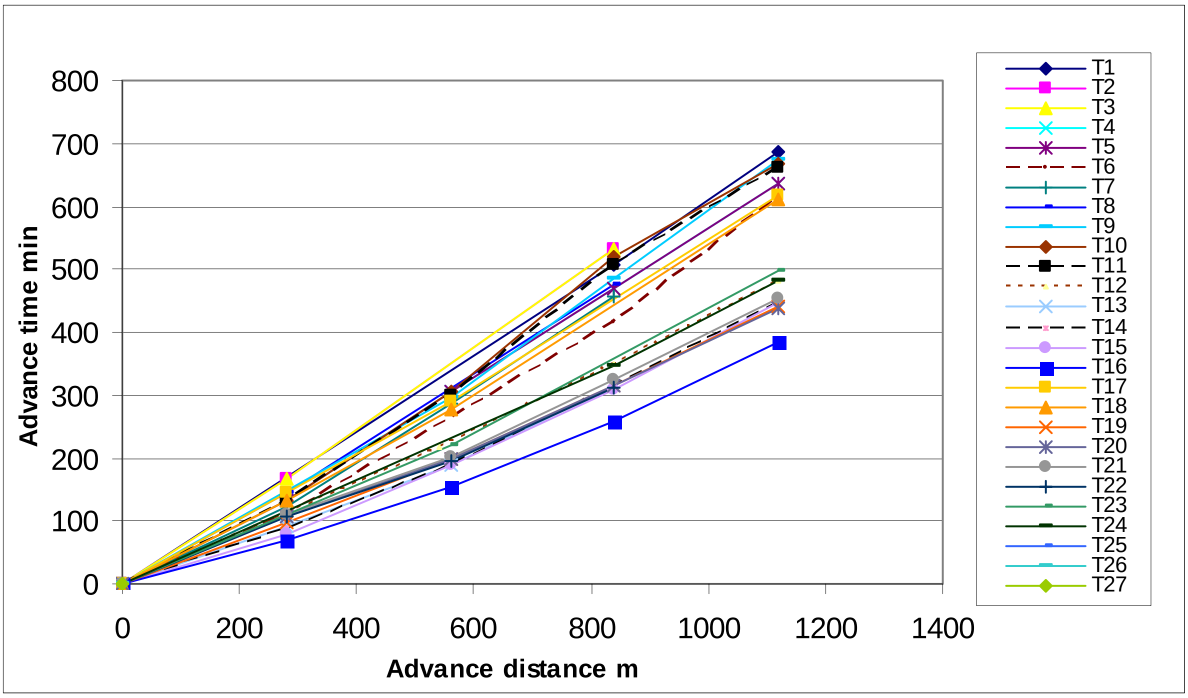



**Figure 7-7 Measured advance curves for field T**

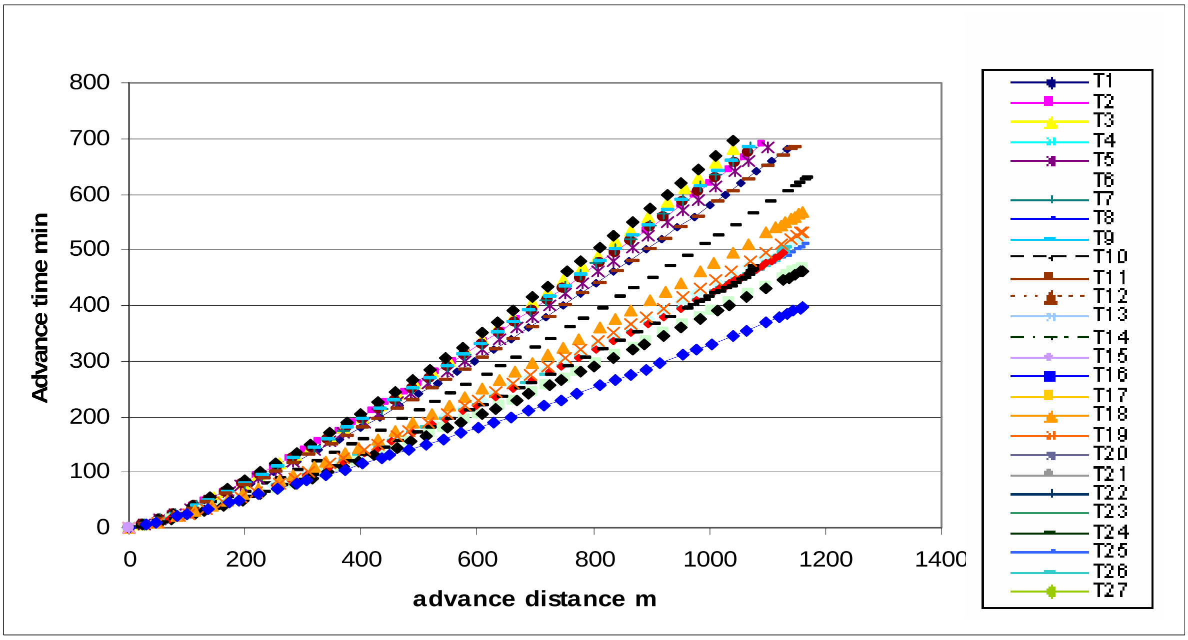



**Figure 7-8 Simulated advance curves for field T using the scaled infiltration**

From these curves (Figures 7.6 and 7.7) it can be seen that the scaled infiltration has reproduced advance trajectories of similar form to the measured trajectories. As expected, the advance trajectories pass through the advance point selected for the infiltration scaling, for example, in the case of selected sample furrows for data sets T1 and T22 as shown in Figure 7.8, but exhibit some small divergence by the end of the field.

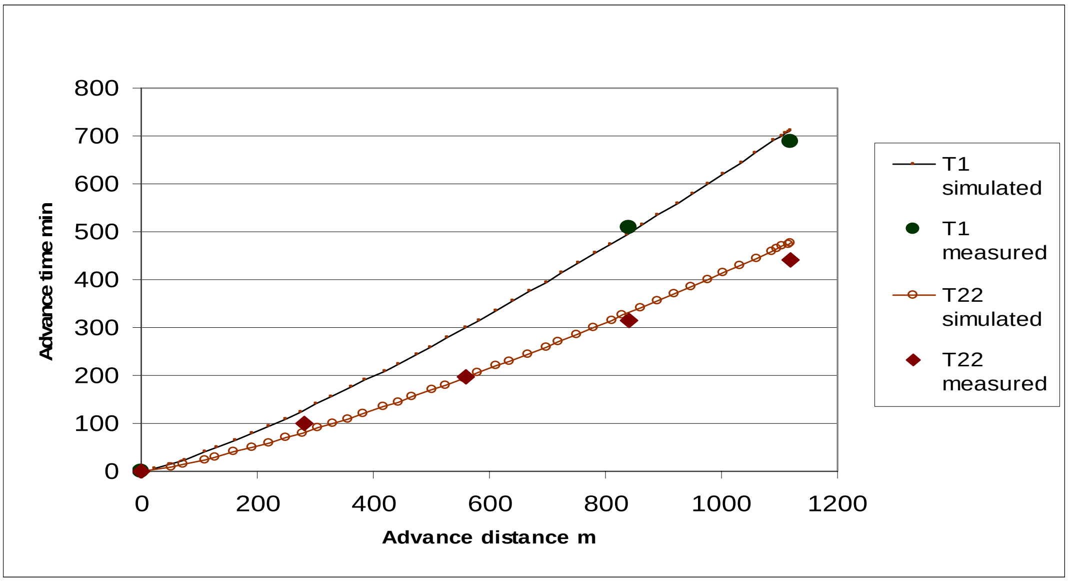



**Figure 7-9 Comparison of measured and simulated advance trajectories for sample furrows**

The trend line analysis (Fig 7.9) for the advance times at the end-points shows a strong correlation between the final measured and the simulated advance times, giving:

$$t_{measured} = 0.955\ t_{simulated}$$

This strong correlation and the reproduction of advance curves by SIRMOD simulations confirms the potential of the scaled infiltration method for the purpose of real-time control.

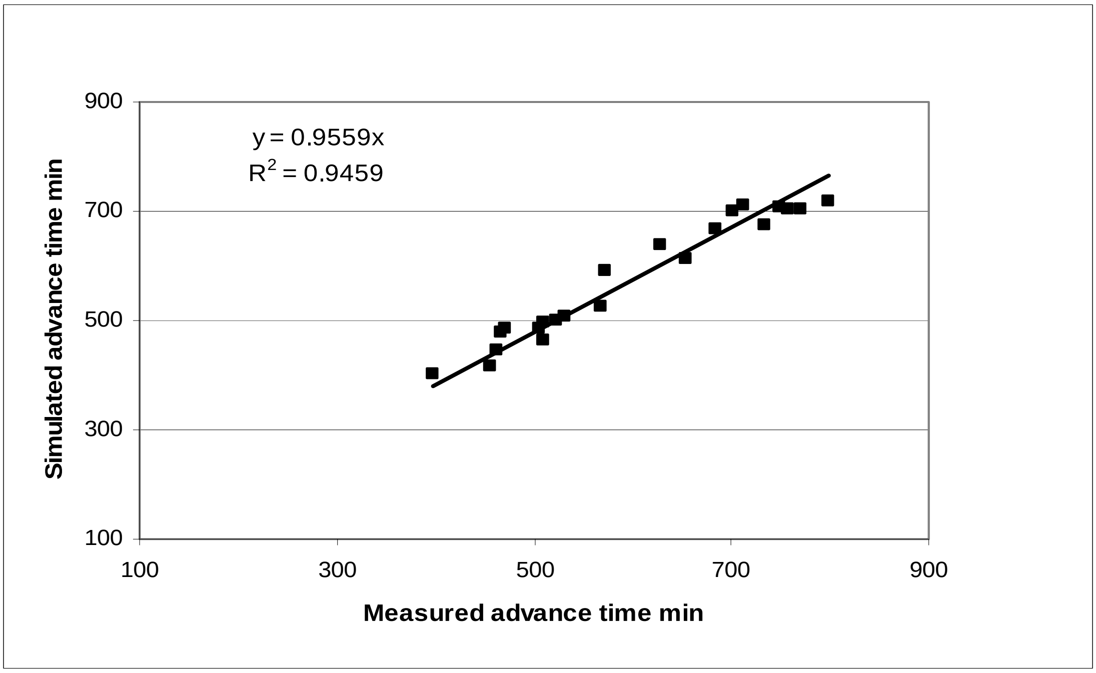



**Figure 7-10 Comparison of final advance times for measured and simulated advance trajectories**

### 7.5.2 Irrigation Performance

The summary of simulated irrigation performance results obtained for the model strategies are shown in Tables 7.1 and 7.2 for fields T and C respectively. The results obtained under each of the model strategies are discussed below.

*Strategies 1 & 2 (Actual irrigation - usual farm management)*

From the summary of simulation results for field T (Table 7.1) it is evident that the overall mean irrigation performance (application efficiency and storage efficiency) of the actual irrigations (strategies 1 and 2) was reasonable (<75%), with a mean application efficiency $E_a$ of 77% and storage efficiency $E_r$ 90%. However, application efficiencies were shown to be highly variable from 50 to 93% (Appendix C Table C.1). Similarly in case of field C the application efficiencies showed considerable variation from 16 to 57% (Appendix C Table C.4), but this field also showed a poorer performance with an overall mean application efficiency of 39% and storage efficiency of 97% (Table 7.2).

## Table 7.1 Summary of irrigation performance under different modelling strategies for field T (means of 27 events).

| **Management/Model strategies** | **$E_a$ (%)** | **$E_r$ (%)** | ***DU* (%)** |
|---|---|---|---|
| Strategy 1 Actual irrigation | 76.8 | 89.9 | 93.4 |
| Strategy 2 Scaled infiltration | 77.4 | 90.8 | 91.7 |
| Strategy 3 Perfect management | 90.8 | 90.9 | 94.0 |
| Strategy 4a Simple recipe management ** | 83.9 | 85.8 | 80.2 |
| Strategy 4b Simple recipe management | 81.9 | 87.6 | 84.5 |
| Strategy 5 Real-time control (scaled infiltration) | 83.3 | 91.9 | 92.2 |
| Strategy 6 Real-time control (actual infiltration) | 83.4 | 91.4 | 92.5 |

** Under this strategy the advance failed to reach the end of the field for six furrows

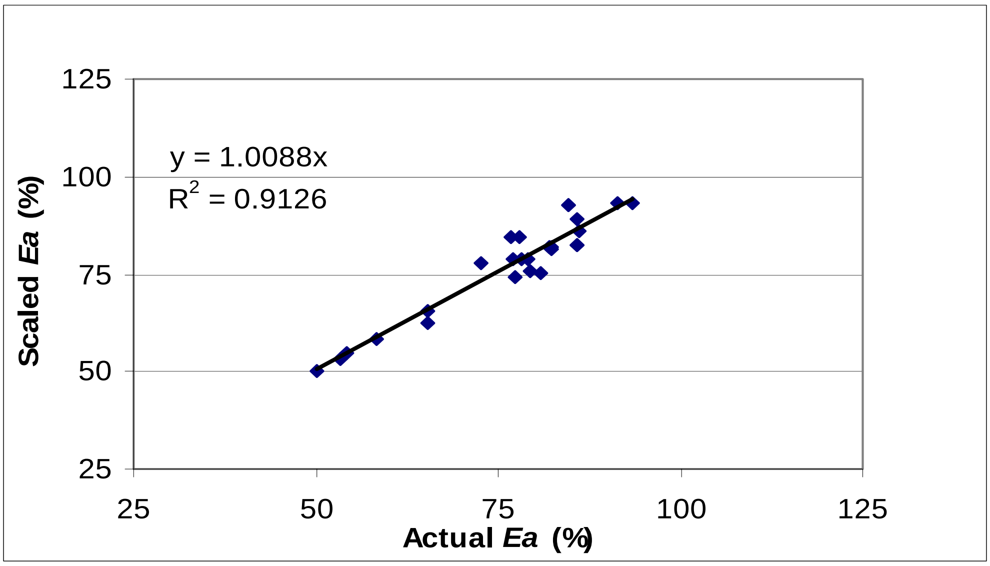
**Table 7.2 Summary of irrigation performance under different modelling strategies for field C (means of 17 events).**

| Management/Model strategies | $E_a$ (%) | $E_r$ (%) | *DU* (%) |
|---|---|---|---|
| Strategy 1 Actual irrigation | 39.1 | 97.9 | 80.2 |
| Strategy 2 Scaled infiltration | 38.2 | 96.9 | 83.9 |
| Strategy 3 Perfect management | 72.1 | 95.1 | 92.5 |
| Strategy 4a Simple recipe management ** | 68.5 | 79.5 | 72.2 |
| Strategy 4b Simple recipe management | 34.4 | 88.6 | 86.6 |
| Strategy 5 Real-time control (scaled infiltration) | 70.2 | 81.3 | 88.5 |
| Strategy 6 Real-time control (actual infiltration) | 70.1 | 80.8 | 90.7 |

** Under this strategy the advance failed to reach the end of the field for eight furrows

For all of the irrigation events, the simulated performance using the scaled infiltration (strategy 2) was similar statistically to the actual performance (strategy 1) for each field as shown for field T in Figure 7.10 (a and b). The results summarized in Tables 7.1 and 7.2 also confirm that the overall mean performance obtained for each field under strategies 1 and 2 is almost identical, reflecting the ability of the scaled infiltration parameters to reproduce the actual irrigations.

(a) Application efficiency




(b) Requirement efficiency

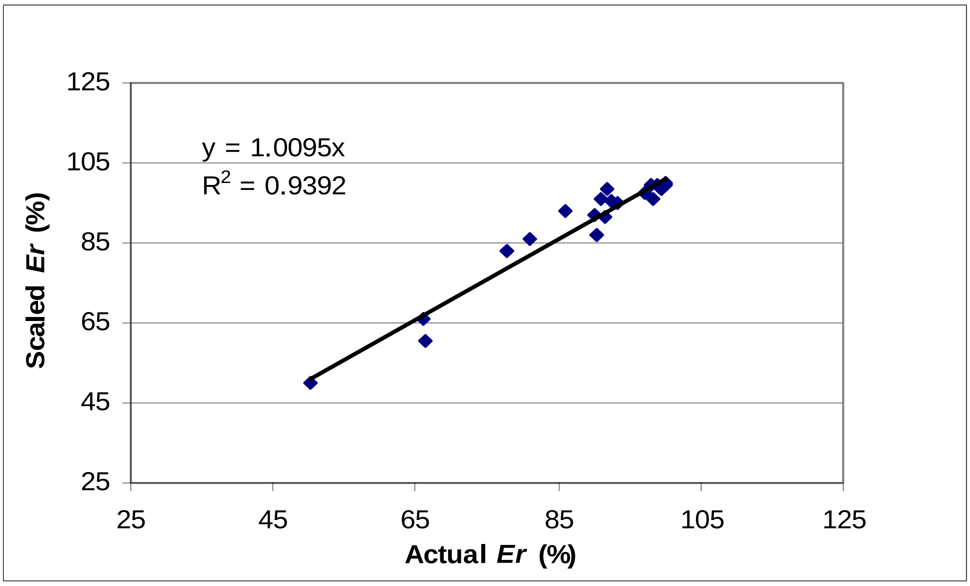



**Figure 7-11 Comparison of irrigation performance results under model strategies 1(actual) and 2 (scaled) for field T.**

*Strategy3 (Perfect Control and Management)*

In this case the INFILT parameters were used and each irrigation event was optimized by varying inflow ($Q_o$) and cut-off time ($t_{co}$) to suit individual soil conditions and furrow characteristics. As expected an excellent performance was obtained for most events. The mean over all irrigation performance ($E_a$ and $E_r$) obtained for all of the irrigation events for field T was above 90% and for field C the $E_a$ was above 72% and $E_r$ 95% as shown in Tables 7.1 and 7.2. This strategy involves the application of more advanced irrigation management practices that may not be possible to be practically implemented in field. The overall best flow rate of 6.5 l/s as observed under this strategy was selected for use in strategies 4b, 5 and 6.

*Strategy 4 a & b (Simple Recipe Management)*

Under strategy 4a a simple recipe management was applied where the cut-off time was fixed equal to 90% of the advance time. The performance was improved but in many events the advance did not reach the end of the field. To overcome this, strategy 4b was applied, using the same parameters as in strategy 4a except that the inflow rate was increased to 6.5 l/s.

The simulation results (Table 7.1) revealed that performance was raised for field T, the application efficiency was improved in most events with a mean of 82% but showed great variation from 55% to 99% (Appendix C Table C.1). Some furrows still faced an incomplete advance. The simple recipe management showed poorer results in case of field C, under both strategies 4a and 4b. The advance was unable reach the end of the field for many of the furrows and yet the field was shown to have low application efficiencies, varying from 15% to 47% (Appendix C Table C.1) with an overall mean of 34% (Table 7.2). Field C poses substantial problems for the irrigation manager because of the extreme variation in the infiltration characteristic across the field, hence its poor response to recipe management.

*Strategies 5 & 6 (Real-time Control)*

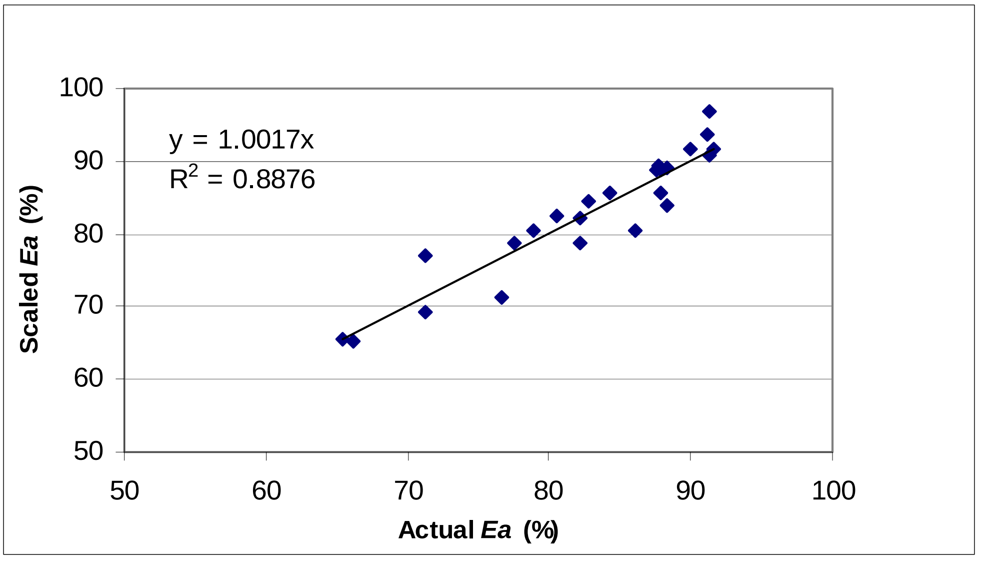
From Tables 7.1 and 7.2 it is evident that the simple real-time control strategy (5) predicts improved performance ($E_a$ and $E_r$) for both fields. For field T the means of the performance measures are $E_a$ 83.3% and $E_r$ 91.9%, with mean $E_a$ of 70.2% and $E_r$ 81.3% for field C.

The actual outcomes from the real-time control strategy as predicted using the actual infiltration parameters (strategy 6) are comparable to those above, with a mean $E_a$ of 83.4%, $E_r$ of 91.4% and $E_a$ 70.1, $E_r$ 80.8% for fields T and C, respectively. This indicates that the mean performance predicted by the real-time control system based on the scaled infiltration is very close to the actual outcomes. The predictions obtained under both strategies for the 44 individual irrigation events are also almost identical to each other, providing further evidence of the equivalence between the scaled and actual infiltration parameters. This is illustrated in the comparison of the application efficiencies predicted under both strategies for individual irrigation events as shown for field T in Table 7.3 and Figure 7.12. Note that the volume of water infiltrated under both strategies is also almost similar (Table 7.3). The results for these strategies show that simple real-time control using the scaled infiltration parameters is feasible and that significant gains in irrigation performance are possible from this system.

**Table 7.3 Volume of water applied and individual irrigation performance for field T under real-time control strategies 5 & 6.**

| $Q_o$ (l/s) | $t_{co}$ (min) | Volume diverted ($m^3$) | Strategy 5 $E_a$ % | Strategy 5 $E_r$ % | Volume infiltrated ($m^3$) | Strategy 6 $E_a$ % | Strategy 6 $E_r$ % | Volume infiltrated ($m^3$) |
|---|---|---|---|---|---|---|---|---|
| 6.5 | 450 | 175.5 | 87.70 | 98.70 | 153.914 | 89.34 | 100 | 156.792 |
| 6.5 | 700 | 273 | 78.87 | 88.70 | 215.315 | 80.33 | 85.84 | 219.301 |
| 6.5 | 675 | 263.25 | 86.02 | 97.61 | 226.448 | 80.6 | 91.46 | 212.180 |
| 6.5 | 485 | 189.15 | 66.13 | 99.85 | 125.085 | 65.36 | 98.68 | 123.628 |
| 6.5 | 620 | 241.8 | 91.61 | 95.48 | 221.513 | 91.65 | 95.52 | 221.610 |
| 6.5 | 625 | 243.75 | 91.26 | 95.88 | 222.446 | 90.87 | 95.48 | 221.496 |
| 6.5 | 625 | 243.75 | 65.37 | 99.32 | 159.339 | 65.48 | 99.96 | 159.608 |
| 6.5 | 650 | 253.5 | 88.37 | 96.56 | 224.018 | 89.13 | 97.39 | 225.945 |
| 6.5 | 635 | 247.65 | 89.98 | 96.05 | 222.835 | 91.54 | 97.71 | 226.699 |
| 6.5 | 450 | 175.5 | 88.32 | 94.1 | 155.002 | 83.87 | 89.36 | 147.192 |
| 6.5 | 500 | 195 | 76.7 | 85.8 | 149.565 | 71.39 | 84.51 | 139.211 |
| 6.5 | 550 | 214.5 | 71.24 | 92.77 | 152.810 | 69.25 | 90.17 | 148.541 |
| 6.5 | 375 | 146.25 | 82.25 | 65.11 | 120.291 | 82.22 | 68.95 | 120.247 |
| 6.5 | 350 | 136.5 | 82.82 | 83.23 | 113.049 | 84.56 | 86.93 | 115.424 |
| 6.5 | 350 | 136.5 | 80.56 | 79.75 | 109.964 | 82.56 | 81.2 | 112.694 |
| 6.5 | 475 | 185.25 | 82.22 | 77.24 | 152.313 | 78.77 | 75.92 | 145.921 |
| 6.5 | 475 | 185.25 | 91.22 | 95.84 | 168.985 | 93.65 | 93.47 | 173.487 |
| 6.5 | 475 | 185.25 | 91.26 | 95.88 | 169.059 | 96.97 | 93.47 | 179.637 |
| 6.5 | 475 | 185.25 | 87.55 | 81.57 | 162.186 | 88.66 | 82.38 | 164.243 |
| 6.5 | 525 | 204.75 | 87.93 | 97 | 180.037 | 85.68 | 94.52 | 175.430 |
| 6.5 | 525 | 204.75 | 84.31 | 97.91 | 172.625 | 85.53 | 99.32 | 175.123 |
| 6.5 | 500 | 195 | 87.94 | 97.26 | 171.483 | 88.94 | 98.37 | 173.433 |
| 6.5 | 475 | 185.25 | 71.26 | 95.86 | 132.009 | 76.97 | 93.45 | 142.587 |
| 6.5 | 475 | 185.25 | 77.52 | 81.55 | 143.606 | 78.65 | 82.36 | 164.224 |
| 6.5 | 525 | 204.75 | 87.92 | 97.3 | 180.016 | 85.66 | 94.54 | 175.389 |
| 6.5 | 525 | 204.75 | 84.34 | 97.92 | 172.686 | 85.56 | 99.33 | 175.184 |
| 6.5 | 500 | 195 | 87.92 | 97.28 | 171.444 | 88.92 | 98.36 | 173.394 |
| **Total** | | **5456.1** | | | **4548.043** | | | **4558.092** |

(a) Application efficiency




(b) Requirement efficiency

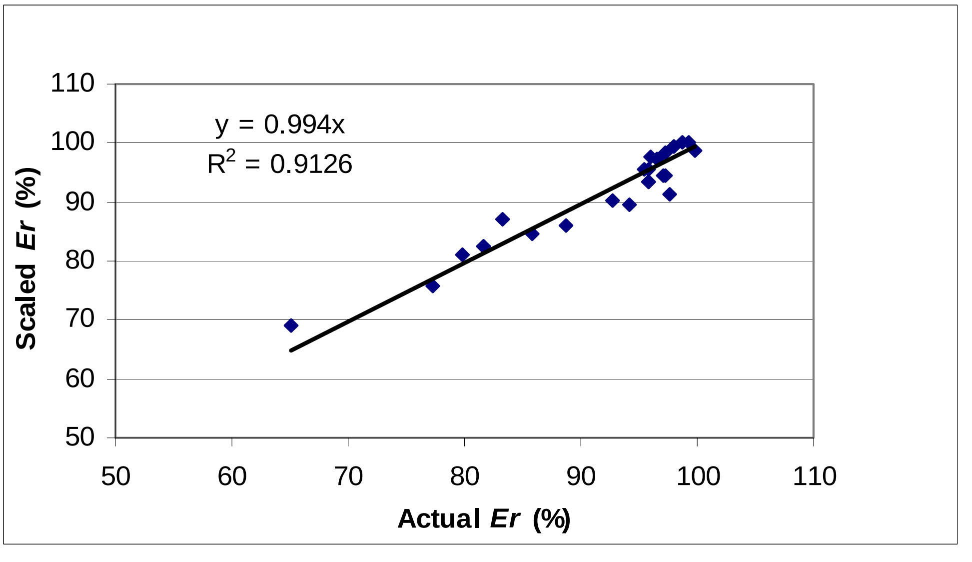



**Figure 7-12 Comparison of irrigation performance simulation results under model strategies 5 (scaled) and 6 (actual) for field T.**

### 7.5.3 Demonstrating water savings from real-time control

The performance simulation results (Tables 7.1 and 7.2) show there is considerable opportunity to improve the irrigation performance obtained under usual farm practices (strategy 1). The recipe management strategies (4a & b) were shown to raise the performance for field T but for some furrows the advance failed to reach the end of the field. However, the recipe management could not bring a simultaneous improvement in the irrigation performance measures for field C. When the real-time control (strategy 5) was applied the overall mean irrigation performance was improved for both fields. A highly significant improvement in irrigation performance was noted in case of field C, with application efficiency increasing from 39% to 70% as shown in Table 7.2, along with acceptable uniformity and storage efficiency. It is evident from these results that the simple real-time control system does have potential to bring significant gains in irrigation performance, with the additional benefit of reducing the volume of water applied per irrigation and deep drainage volumes, thus reducing the potential for environmental harm.

Table 7.4 presents the total volumes of water applied to the 44 furrows on fields T and C under usual farm management and real-time control. These 44 furrows cover an area of 7.1 ha, which is comprised of 27 furrows, 1160 m long with 2 m spacing and 17 furrows, 240 m long with 2 m spacing for field T and C respectively.

It can be seen from the table 7.4 that the volume of water actually applied to the 44 furrows on fields T and C under usual farm management was 7285 $m^3$ but it could be reduced to 6046 $m^3$ under real-time control. This indicates the substantial potential savings of 1239 $m^3$ (1.239 Ml) of volume of water per irrigation over an area of 7.1 ha, which is a significant loss of water to the grower. For Queensland cotton growers usually applying 6 to 8 irrigations annually this represents an annual water saving of 1.10 to 1.40 Ml/ha (equivalent to 17.4 mm per irrigation) that can be used beneficially to grow more crop, clearly indicating the substantial benefits that are achievable in the irrigation industry by implementing simple real-time control.

**Table 7.4 Summary of volumes of water applied to fields T and C under usual farm management and real-time control.**

| Field | Water applied under usual farm management ($m^3$) | Water applied under real-time control ($m^3$) | Water savings due to real-time control ($m^3$) |
|---|---|---|---|
| Field T | 5794 | 5456 | 338 |
| Field C | 1491 | 590 | 901 |
| Total | 7285 | 6046 | 1239 |

## 7.6. Conclusions

A simple practical system for real-time control of furrow irrigation that varies only the time to cut-off is proposed. To evaluate the method, the SIRMOD model was used to simulate the irrigation performance for two fields, for a range of irrigation strategies using both the scaled and the actual infiltration parameters. One of the strategies included in the simulations was the proposed real-time control strategy.

It is concluded that:

- the measured advance curves and measured irrigation performance were able to be reproduced with sufficient accuracy using the scaled infiltration parameters,
- the simple real-time control strategy is feasible and has the potential to bring significant improvements in irrigation performance over that achieved under simple recipe management or current farmer management, and
- substantial reductions in the total volume of water applied per irrigation are achievable, that could be used beneficially to grow a greater area of crop.

# Chapter 8

# Conclusions and Recommendations

## 8.1 Review of research

Amongst surface irrigation systems, furrow irrigation is the most commonly used method for irrigating crops and pastures in Australia and all around the world but this method has been often considered inefficient with highly variable and poor application efficiencies. In fact it is not the fault of method but indeed it is the lack of proper management and a limited capability to predict the soil infiltration characteristic. The infiltration characteristic of the soil is the dominant of all the factors affecting the performance of surface irrigation and both spatial and temporal variations in the infiltration characteristic are a major physical constraint to achieving higher irrigation application efficiencies.

Real-time optimisation and control has the potential to overcome these spatial and temporal variations and return highly significant improvements in performance. Calculation of the infiltration parameters from irrigation advance data is now the preferred method. Substantial work has been directed towards developing methods to measure the infiltration properties of the soil. However the greatest limitation of the existing methods is that they are data intensive and or unreliable and provide soil infiltration properties after an irrigation event. Intensive data requirement is also a major hindrance towards implementing a simple real time control.

The infiltration characteristics of the soil usually are different for each irrigation, the reason is that conditions change for subsequent irrigations (e.g., different initial soil moisture, different surface conditions and different discharge). Hence the set of infiltration parameters calibrated with data collected during an irrigation are not suitable for predicting subsequent irrigations. An *a posterior* evaluation method is not suitable for optimization of irrigations.

This PhD study addressed these issues successfully in three key chapters 5, 6 and 7 of this dissertation that are focussed on:

- Evaluation of current infiltration estimation techniques
- Development and evaluation of a novel real-time infiltration model
- Demonstrating the potential gains from simple real-time control

## 8.2 Major outcomes and key findings

The major outcomes and key findings are given in the following sections according to the issues addressed in this research study.

### 8.2.1 Evaluation of current infiltration estimation techniques

Knowledge of the spatial average value of infiltration characteristic is required for the accurate simulation and optimisation of surface irrigation. Substantial recent work has been directed towards developing methods to measure the infiltration properties of the soil. Solution of the inverse problem has generated most interest that is, determining the infiltration parameter values from the measured surface irrigation advance.

A number of methods are available based on the volume balance model. Data requirements for the models vary considerably, and some condition or constrain the solution to reduce the requirement for data, but in ways that may limit application of the method to certain soils and situations. Many of the methods have only been tested on a limited range of soil types and conditions, typically for low flow rates in short furrows and relatively light textured soils. Hence the applicability, accuracy and robustness of the models have not been proved adequately. There is a requirement for an accurate and robust method for determining the infiltration characteristic from an absolute minimum of field data. Six competing methods were selected to evaluate their ability to accommodate the long furrows and long irrigation durations common in northern Australia and be able to describe the infiltration characteristics of the predominant heavy clay (cracking) soils. Under this study the selected methods were tested on data sets from 10 irrigation events collected under different furrow characteristics and a range of inflow rates on heavy clay soils in the Queensland cotton and sugar growing areas. The key findings from the results of this evaluation study are drawn below.

Of the methods tested, the INFILT program was shown to be the most accurate and versatile method. It was rated ahead of the previously favoured two-point method because prior measurements of the steady infiltration rate are not required. This more than compensates for the additional advance points required by INFILT.

The linear infiltration function was shown to provide a reasonable description of the infiltration characteristics of most of the soils studied. The reduced data requirement to obtain the two parameters of this function (compared with INFILT and the two-point method) makes it worthy of further consideration.

The method developed by Upadhyaya and Raghuwanshi (1999) was shown to be unsuitable for the soils used in this study. The exponential representation of the advance trajectory offers considerable potential over the power curve but the relationship between the exponent in the infiltration function and that in the advance function needs further exploration.

The one-point methods of Valiantzas (2001) and Shepard *et al.* (1993) were also not suitable on the soils studied. Over-conditioning of the solution in both cases rendered them inappropriate for the heavy often cracking clay soils of this project.

Finally none of the methods tested were entirely suitable for use in a real time control system where the requirement is for applicability to a wide range of soils and minimum advance data preferably obtained early in the irrigation. However, INFILT and the linear infiltration function have the potential to be used in the real time control provided a sufficient number of advance points are obtained.

There remains a pressing need to develop a new technique or model which requires less advance data collected early in the advance and which can provide infiltration parameters in real-time and without significant loss of accuracy. This would provide equipment and labour cost advantages by enabling the sensors to be left in the field throughout the whole irrigation season (as opposed to only 1 to 3 irrigations per season at present). The use of fewer in-field sensors means that it would be a cost effective and rapid tool in providing data for real-time control and optimization of surface irrigated fields.

### 8.2.2 Development and evaluation of a real-time infiltration model (REIP)

Under this study a new method for the real-time estimation of infiltration parameters (REIP) has been developed for the prediction of soil infiltration parameters in real-time from a minimum of furrow irrigation advance data.

The underlying hypothesis for the method is 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. For the purpose of real time control, the data required for obtaining soil infiltration characteristics for the irrigated furrows are reduced by scaling the infiltration parameters from an infiltration curve of known shape and one advance point measurement in each furrow. In this process a model infiltration curve (MIC), a new concept, is introduced. A furrow in the field is selected as the model furrow and its parameters in the Kostiakov-Lewis equation are calculated from extensive advance and run-off data. The cumulative infiltration curve calculated from these parameters is the model infiltration curve. Subsequently the model infiltration curve parameters can be used to estimate (by scaling) the cumulative infiltration curves for the whole field, and other irrigation events, using only one advance point for each of the remaining furrows or for each subsequent irrigation event.

The proposed method was evaluated using data from 44 irrigation events from two fields having contrasting infiltration characteristics and for which extensive advance data were available. The data for each field encompassed multiple furrows and multiple irrigations and defined the extent of the spatial and temporal variability in the infiltration at each site.

The results of this evaluation study indicated that:

- The scaled infiltration curves given by the REIP method were of similar shape to the actual curves and gave nearly identical depths of infiltration up to the advance time for each furrow.

- The mean and variance of the scaled and actual infiltration at various times up to measured advance times were found similar.

- The method was not sensitive to the choice of furrow used to give the model infiltration curve. However the model infiltration curve has a critical role in the process so the accuracy of the method is related to the accuracy of the model curve, hence the model furrow should be evaluated using full advance data including runoff and, if available, the full inflow hydrograph.

On the basis of these results it can be concluded that the proposed method has the potential for use in real time control and management of furrow irrigation.

### 8.2.3 Demonstrating the potential gains from simple real-time control

A simple practical system for real-time control of furrow irrigation that varies only the time to cut-off was evaluated. The system predicts the infiltration characteristics of the soil in real-time using data measured during an irrigation event, simulates the irrigation, and determines the optimum time to cut-off for that irrigation. To evaluate the system, the SIRMOD model was used to simulate the irrigation performance for the two fields from the previous section, for a range of irrigation modelling strategies using both the scaled and the actual infiltration parameters. One of the strategies included in the simulations was the proposed real-time control strategy.

From the simulation results it was shown that the measured advance curves and measured irrigation performance were able to be reproduced with sufficient accuracy using the scaled infiltration parameters. This confirmed the quality and credibility of the scaled infiltration given by the REIP method.

It was further concluded that the simple real-time control strategy is feasible and has the potential to bring significant improvements in irrigation performance over that achieved under simple recipe management or current farmer management.

By adopting a simple real-time control, significant reductions in the total volume of water applied per irrigation are achievable, that could be used beneficially to grow a greater area of crop. Over the area of 7.1 ha represented by the 44 furrows evaluated, 1239 $m^3$ of water can be saved per irrigation which is a substantial seasonal saving of 1.10 to 1.40 Ml/ha.

## 8.3 Practical application of simple real-time control

### 8.3.1 Introduction

The Australian cotton industry is predominantly irrigated by furrow irrigation, which is used by over 90% of the Australian cotton growers (Foley & Raine, 2001). Improved performance during furrow irrigation with siphons typically involves higher flow rates using larger or multiple siphons over shorter times as observed across the industry (Purcell, 2004). Consequently, irrigators aiming to improve the performance of the systems to achieve increased water use efficiency (WUE) require further intensification of an already labour intensive system at a time when there is a dwindling supply of labour force.

As a result there has been an increased interest in less labour intensive irrigation systems those do not require siphons employed. Overhead and drip irrigation have been used for some time in order to combat the issues of limited water and labour (Raine *et. al.,* 2000; Foley & Raine, 2001). Pipes through the bank have also been used as a less labour intensive furrow irrigated system. Bay irrigation, although quite prevalent in other industries (rice and pasture), has been used more recently by cotton irrigators with some modifications (Grabham & Williams, 2005). These bay irrigations systems with bank-less channel features were installed because they were expected to be less labour intensive.

There is a lack of data about how the water use efficiency of these alternatives compare to that of furrow irrigated systems and the potential for optimisation of each system (Raine *et al.,* 2000). However, as furrow irrigation remains the dominant irrigation method in the Australian cotton industry efforts towards improving the performance and profit per megalitre of this system still remains of paramount importance.

The feasibility of a simple real-time control system for furrow irrigation has been demonstrated by the work reported in Chapters 6 and 7 of this dissertation. Application of the system in the field involves the application of a number of steps: characterisation of the field, control and measurement of the furrow inflow, measurement of the advance and infiltration estimation, and simulation and optimisation for selection of the optimum time to cut-off. The system has been kept simple by varying only cut-off time to encourage implementation of the system. It could be applied as a manual or automated system. The following sections describe how this system might be applied and the tools necessary for its application.

### 8.3.2 Characterisation of field

The field will be physically characterised by quantifying the field data including, field length, longitudinal slope, field deficit, furrow geometry or cross-section and model furrow selected for the field. These data are necessary for the accurate simulation of the surface irrigation hydraulics.

The infiltration characteristic of the furrow selected as the model furrow must be determined as accurately as possible using the best available method. At present this should involve the use of extensive advance and runoff data, and where possible a full inflow hydrograph, in the IPARM program of Gillies and Smith (2007).

The deficit can be estimated by usual techniques like soil moisture probes, or from evapotranspiration. For cracking clay soils (like field T analysed under this study) there is a linear relationship between crack fill and soil water deficit, for example, Robertson *et al.* (2004) have suggested that the deficit can be considered as 4/3 of the crack fill volume. With further work it may be possible to infer the deficit in real time from the scaled infiltration characteristic.

### 8.3.3 Control and measurement of inflow

The features required for the inflow control include:

- operation of the furrows in sets;
- rapid start up and shut down of flow;
- adjustable flow rate (between irrigations);
- flow constant with time;
- flow rate same in each furrow; and
- automated measurement of the inflow.

These features cannot be obtained by the traditional over-bank siphon systems but can be provided by gated pipe (rigid or flexible). Gated pipe inflow systems are commonly used to distribute water in furrow irrigation. In Australia they are used in the sugar industry but are rarely found in other surface irrigated cropping systems. Compared to traditionally used siphon application systems they offer labour savings and the potential for automation. Rigid and flexible / layflat gated pipes are typically operated under low pressure conditions (Smith 1988, 1990) and therefore the kinetic energy term become particularly important when modelling the flow. Original research was undertaken by Smith *et al.* (1986) to verify the relationships between pipeline pressure, energy and outlet flow-rate in both rigid and layflat pipes, resulting in a simple software tool known as GPipe.

GPipe can be used as a design tool to select appropriate combinations of pipe length, diameter, gate area, gate spacing and pressure to give the desired discharge to the group of furrows. During operation, the discharge or flow from each gate can be inferred in real-time using GPipe from measurement of pressure in the pipe.

### 8.3.4 Estimation of infiltration

The scaling technique REIP is proposed for real time prediction of infiltration properties of the individual furrows or sets of furrows. This technique is fully described in Chapter 6 of this dissertation and requires no further discussion here.

### 8.3.5 Simulation and optimisation

Recent work by Gillies (2006) has resulted in the development of a unique model IrriProb, based on the furrow irrigation simulation model FIDO of McClymont *et al,* (2002), which allows simulation and optimisation of the performance of a group of furrows or whole field. IrriProb is an appropriate option for use in real-time optimisation and control of individual irrigation events for sets of furrows. The model can execute simulations of the individual furrows in a set for a range of inflow rates and cut off times. More importantly it also includes a tool to arrive at the inflow rate and cut off time that gives optimal performance for the set as a whole.

Knowing the infiltration characteristic for the model furrow and the variability in infiltration for the set of furrows (from previous irrigations or by the scaling method), the optimum cut-off time for the set of furrows can be predicted and the flow can be turned off accordingly to control the irrigation and achieve optimum performance.

## 8.4 Other recommendations for further research

During the course of this PhD study it has become evident that the simple real-time control system proposed has the potential to bring about significant improvements in irrigation performance. The system has been evaluated using existing data from the two fields with contrasting infiltration characteristics. Prototyping of the system in the field is the significant next step in the progress of the research. Other lesser areas identified for further research are:

- further refinement and validation of the tools for infiltration evaluation;
- investigation of alternative methods of scaling that might be applicable to different soils;
- testing the REIP method on different soils and situations; and
- further investigation of the scaling factor and the causes of its variation with advance distance.

# REFERENCES

Allen, R. R., & Musick, J. T. (1992). Furrow traffic and ripping for control of irrigation intake. Applied Engineering in Agriculture 8(2), 243-248.

Allen, R. R., & Musick, J. T. (1997). Furrow irrigation intake with multiple traffic and increased axle mass. Applied Engineering in Agriculture, 13(1), 49-53.

Anthony, D. (1995). On-farm water productivity, current and potential: options, outcomes, costs. Irrigation Australia, 10, 20-23.

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

Azevedo, C. A. V., Merkley, G. P., & Walker, W. R. (1996, 11-14 June). Surface irrigation real-time optimization model (SIRTOM). Paper presented at the ASAE Conference on Computers in Agriculture, Cancun, Mexico.

Bali, K., & Wallender, W. W. (1987). Water application under varrying soil and intake oppurtunity time. Trans of the ASAE, 30(2), 442-448.

Baustista, E., & Wallender, W. W. (1985). Spatial variability of infiltration in furrows. Trans of the ASAE, 28(6), 1851-1855.

Baustista, E., & Wallender, W. W. (1991). Optimisation of furrow infiltration parameters from advance times and advance rates. Paper presented at the ASCE National Conference, NewYork, USA.

Baustista, E., & Wallender, W. W. (1992). Hydrodynamic furrow irrigation model with specified space steps Journal of Irrigation and Drainage Engineering, ASCE, 118(3), 450-465.

Bautista, E., & Wallender, W. W. (1993). Reliability of optimised furrow infiltration parameters. Irrigation and Drainage, 119(5), 784-800.

Blackwell, P. J., Ward, M. A., Lefevere, R. N., & Cowan, D. J. (1985). Compaction of swelling clay soil by agriculture traffic:effects upon coditions for growth of winter cereals and evidence for some recovery of structure. Journal of Soil Scince, 36, 633-640.

Burt, C. M., Robb, G. A., & Manon, A. (1982). Rapid evaluation of furrow irrigation efficiencies. Paper presented at the American Society of Agricultural Engineers (ASAE) National Meeting. Paper No. 82-2537, St. Joseph, Mich, USA.

Camecho, E., Lucena, C. P., Canas, J. R., & Alcaide, M. (1997). Model for management and control of furrow irrigation in real-time. Journal of Irrigation and Drainage Engineering, 123(4), 264-269.

Cavero, J., Playan, E., Zapata, N., & Faci, J. M. (2001). Simulation of maize grain yield variability within a surface-irrigated field  Agronomy Journal, 93(4), 773-782.

Childs, J. L., Wallender, W. W., & Hopmans, J. W. (1993). Spatial and seasonal variation of furrow infiltration. Journal of Irrigation and Drainage Div: ASCE, 119(1), 74-90.

Christiansen, J. E., Bishop, A. A., Kiefer, F. W., & Fok, Y. S. (1966). Evaluation of intake rate constants as related to advance of water in surface irrigation. Trans of the ASAE, 9(5), 671-674.

Clemens, A. J. (1981). Evaluation of infiltration measurements for border irrigation. Agricultural Water Management, 3(4), 251-267.

Clemens, A. J. (1983). Infiltration equations for border irrigation models. Paper presented at the ASAE Conference: Advances in infiltration, Chicago, IL, USA.

Clemens, A. J. (1988). Method for analysing field scale surface irrigation uniformity. Journal of Irrigation and Drainage Engineering, ASCE, 114(1), 74-88.

Collis-George, N. (1977). Infitration equation for simple soil system. Water Resources Research, 13, 395-403.

Collis-George, N., & Greene, R. S. B. (1979). The effect of aggregate size on the infiltration behavior of a slaking soil and its relevance to ponded irrigation. Australian Journal of Soil Research, 17, 65-73.

Dagan, G., & Bresler, E. (1983). Unsaturated flow in spatially variable fields-1. Derivation of models of infiltration and redistribution. Water Resources Research, 19(2), 413-420.

Dalton, P., Raine, S. R., & Broadfoot, K. (2001). Best management practices for maximising whole farm irrigation efficiency in the Australian cotton industry: Final report to the Cotton Research and Development Corporation, National Centre for Engineering in Agriculture Report 179707/2, USQ, Toowoomba.

Elliott, R. L., & Walker, W. R. (1980). Furrow irrigation infiltration and advance functions. Paper presented at the American Society of Agric. Engineers National Meeting. St. Joseph, Mich., USA. Paper No. 80-2075.

Elliott, R. L., & Walker, W. R. (1982). Field evaluation of furrow irrigation and advance functions. Trans. of the ASAE, 25(6), 396-400.

Elliott, R. L., Walker, W. R., & Skogerboe, G. V. (1982). Zero inertia modelling of furrow irrigation advance. Journal of irrigation & Drainage Engineering, ASCE 108(IR3), 179-195.

Elliott, R. L., Walker, W. R., & Skogerboe, G. V. (1983). Infiltration parameters from furrow irrigation advance data. Trans of the ASAE, 26(6), 1726-1731.

Enciso-Medina, J., Martin, D., & Eisenhauer, D. (1998). Infiltration model for furrow irrigation. Journal of Irrgation and Drainage Engineering, ASCE, 124(2), 73-80.

Esfandiari, M., & Maheshwari, B. L. (1997). Application of the optimization method for estimating infiltration characteristics in furrow irrigation and its comparison with other methods. Agricultural Water Management, 34(2).

Evans, R. G., Smith, C. J., Oster, J. D., & Myer, B. A. (1990). Saline water application effects on furrow infiltration of red-brown earths. Trans of the ASAE, 33 1563 – 1572.

Fang, X. Y. U., & Singh, V. P. (1990). Analytical model for furrow irrigation. Journal of Irrigation and Drainage Engineering, ASCE, 116(2), 154-170.

Fangmeier, D., & Ramsey, M. (1978). Intake characteristics of irrigation furrows. Trans of the ASAE, 21(4), 694-700.

Fattah, H. A., & Upadhyaya, S. K. (1996). Effect of soil crust and soil compaction on infiltration in a Yolo loam soil. Transactions of the ASAE 39(1), 79-84.

Foley, J. P., & Raine, S. R. (2001). Centre Pivot and Lateral Move Machines in the Australian Cotton Industry. National Centre for Engineering in Agriculture (NCEA), Toowoomba, USQ. Publication No. 1000176/1.

Gillies, M. H. (2006). Managing the effect of infiltration variability on the performance of surface irrigation. PhD Thesis, University of Southern Queensland Toowoomba, QLD, Australia.

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

Gillies, M. H., Smith, R. J., & Raine, S. R. (2007). Accounting for temporal inflow variation in the inverse solution for infiltration in surface irrigation. Irrigation Science, 25(2).

Grabham, M., & Williams, D. (2005). Bankless channel irrigation: An update. The Australian Cotton grower. 26(3) pp 18 – 19.

Hanson, B., & Schwankl, L. (1994). Water management manual, University of California (UC), Davis. WM Series publication No, 94(1).

Haverkamp, R., Kutilek, M., Parlange, J. Y., Rendon, L., & Krejca, M. (1988). Infiltration under ponded conditions: 2, Infiltration equations tested for parameter time-dependance and predictive use. Soil Science Society of America Journal, 145(5), 327-329.

Hillel, D. (1980). Fundamentals of soil physics: Academic Press Inc., New York, USA.

Horton, R. E. (1940). An approach towards a physical interpretation of infiltration capacity. Soil Science Society of America Journal, 5, 399-417.

Hunsaker, D. J., Clemmens, A. J., & Fangmeier, D. D. (1999). Cultural and irrigation management effects on infiltration, soil roughness, and advance in furrowed level basins. Trans of the ASAE, 42(6), 1753-1764.

ICID, C. (2006). Use of water and land for food security and environmental sustainability. Irrigation and Drainage, 55, 217-218.

Isbell, R. F. (1996). The Australian soil classification: CSIRO Publishing, Collingwood, Victoria, Australia, 143 pp.

Izadi, B., & Wallender, W. W. (1985). Furrow hydraulic characteristics and infiltration. Trans of the ASAE, 28(6), 1901-1908.

Jaynes, D. B., & Clemmens, A. J. (1986). Accounting for spatially variable infiltration in border irrigation models. Water Resources Research, 22(8), 1257-1262.

Kemper, W. D., & Rosenau, R. C. (1984). Soil cohesion as affected by time and water content. Soil Science Society of America Journal, 48, 1001-1006.

Kostiakov, A. N. (1932). On the dynamics of the coefficient of water percolation in soils and the necessity for studying it from a dynamic point of view for purposes of amelioration. Trans. Sixth Comm. Intern. Sot. Soil Sciences, Part A, 17-12.

Kruse, E. G., & Heermann, D. F. (1977). Implications of Irrigation system efficiencies. Journal of Soil and Water Conservation, 32(6), 465-470.

Lamacq, S., & Wallender, W. W. (1994). Soil water model for evaluating water delivery flexibility. Journal of Irrigation and Drainage Engineering, ASCE, 120(4), 756-774.

Larry, G. J. (1988). Principles of farm irrigation system design. Wiley international edition. John Wiley & Sons. Inc. Washington State Univesity: New York, 302-303.

Latif, M., & Sajid, M. (2004). Field measurement and simulation of advance rates for continuous and surge irrigated furrows in Pakistan. Irrigation & Drainage, 53, 437–447.

Lewis, M. K. (1937). The rate of infiltration of water in irrigation practice. Trans. Am. Geophys. Union 18th Annual Meeting, 34-47.

Lewis, M. R., & Milne, W. E. (1938). Analysis of border irrigation. Agricultural Engineering 19, 267-272.

Maheshwari, B. L., & Jayawardane, N. S. (1992). Infiltration characteristics of some clayey soils measured during border irrigation. Agricutural Water Management 21(265-279).

Maheshwari, B. L., & McMahon, T. A. (1993a). Performance evaluation of border irrigation models for South–East Australia: Part 1, Overall suitability for field applications. Journal of Agricultural Engineering Research, 54, 127-139.

Maheshwari, B. L., & McMahon, T. A. (1993b). Performance evaluation of border irrigation models for South-East Australia Part II, Advance and Recession Characteristics. Journal of Agricultural Engineering Research, 54, 67-87.

Maheshwari, B. L., Turner, A. K., McMahon, T. A., & Cambell, B. J. (1988). An optimisation technique for estimating infiltration characteristics in border irrigation. Agricultural Water Management, 13, 13:24.

Mailhol, J. C. (2003). Validation of a predictive form of Horton infiltration for simulating furrow irrigation. Journal of Irrigation and Drainage Engineering, ASCE, 129(6), 412-421.

Mailhol, J. C., Baqri, M., & Lachhab, M. (1997). Operative irrigation modelling for real-time applications on closed-end furrows. Irrigation and Drainage Systems, 11, 347-366.

Mailhol, J. C., Priol, M., & Benali, M. (1999). A furrow irrigation model to improve irrigation practices in the Gharb valley of Morocco. Agricultural Water Management, 42, 65-80.

McClymont, D. J., Raine, S. R., & Smith, R. J. (1996). The prediction of furrow irrigation performance using the surface irrigation model SIRMOD. Paper presented at the Irrigation Association of Australia, May 1996, Adelaide.

McClymont, D. J., Raine, S. R., & Smith, R. J. (2002). An integrated numerical model for the design and management of furrow Irrigation. Paper presented at the 2nd International Conference on Multiple Objective Decision Support Systems for Land, Water and Environment Management, Brisbane, Australia.

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

Merriam, J. L., & Keller, J. (1978). Farm irrigation system evaluation: A guide for management: Agricultural and Irrigation Engineering Department, Utah State University, Logan, Utah.271-273.

Michael, A. M. (1999). Irrigation: Theory and Practice: Vikas publishing house Pvt. Ltd Masjid road, Jangapura, New Delhi, India.546-547.

Mitchell, A. R., & Genuchten, M. T. v. (1993). Flood irrigation of a cracked soil. Soil Science Society of America Journal, 57, 490 – 497.

Nachabe, M. H. (1996). Microscopic capillary length, sorptivity, and shape factor in modelling the infiltration rate. Soil Science Society of American Journal, 60(4), 957-961.

Norum, D. I., & Gray, D. M. (1970). Infiltration equations from rate of advance data. Journal Irrigation and Drainage Engineering, ASCE, 96(2), 111-119.

NRM (2003). International year of fresh water. Natural Resources and Mines (NRM), Queensland, Australia. Retrieved 25 June, 2005, from www.nrm.qld.gov.au/water

Or, D. (1996). Wetting-induced soil structural changes. The theory of liquid phase sintering. Water Resources Research, 3041-3049., 2(10).

Oyonarte, N. A., Mateos, L. and Palomo, M.J. (2002). Infiltration variability in furrow irrigation. Journal of Irrigation and Drainage Engineering, 128(1), 26-33.

Philip, J. R. (1957). Theory of infiltration: 4. Soil Science Society of America Journal, 84(3), 257-264.

Philip, J. R., & Farrell, D. A. (1964). General solution of the infiltration–advance problem in irrigation hydraulics. Journal of Geophys. Research., 69, 621-631.

Playan, E., & Zapata, N. (2000). Simulating elevation and infiltration in level-basin irrigation. Journal of Irrigation and Drainage Engineering, ASCE, 126(2), 78-84.

Purcell, J. (2004). Doing better with what we have: the art of surface irrigation: The Australian Cotton grower Publication. 24(7) pp 36 – 38.

Purkey, D., & Wallender, W. W. (1989). Surge flow infiltration variability. Trans of the ASAE, 32(3), 894-900.

Raine, S. R., Foley, JP., and CR. Henkel (2000). Drip irrigation in the Australian cotton industry: a scoping study: National Centre for Engineering in Agriculture (NCEA), USQ, Toowoomba, QLD, Australia. Publication No. 179757/1.

Raine, S. R., & Bakker, D. M. (1996). Increased furrow irrigation efficiency through better design and management of cane fields. Proceedings of Australian Society of Sugarcane Technologists. 119-124.

Raine, S. R., McClymont, D. J., & Smith, R. J. (1997). The development of guidelines for surface irrigation in areas with variable infiltration. Proceedings of Australian Society of Sugercane Technologists. 293-301.

Rayej, M., & Wallender, W. W. (1988). Time solution of kinematic-wave model with stochastic infiltration. Journal of Irrigation and Drainage, 114 (4), 605-619.

Reddell, D. L., & Latortue, H. F. (1986). Evaluation of furrow surface storage and Kostiakov infiltration parameters using irrigation advance data. Paper presented at the National Meeting American Society of Agricultural Engineers (ASAE), St. Joseph, Mich. Paper No. 86-2874.

Redell, D. L. (1981). Modified rate of advance method for an automatic furrow irrigation system. Paper presented at the American Society of Agricultural Engineers (ASAE) National Meeting, St. Joseph, Mich. Paper No. 81-2552.

Renault, D., & Wallender, W. W. (1992). ALIVE (Advance linear velocity): Surface irrigation rate balance theory. Journal of Irrigation and Drainage, 118(1), 138-155.

Renault, D., & Wallender, W. W. (1996). Initial-inflow-variation impacts on furrow irrigation evaluation. Journal of Irrigation and Drainage Engineering, ASCE, 122(1), 7-14.

Renault, D., & Wallender, W. W. (1997). Surface storage in furrow irrigation evaluation. Journal of Irrigation and Drainage Engineering, ASCE, 123(6), 415-422.

Robertson, D., Wood, M., & Wang, Q. J. (2004). Estimating hydraulic parameters for a surface irrigation model from field conditions. Australian Journal of Experimental Agriculture, 44, 173-179.

Saleh, A., & Hanks, R. J. (1989). Field evaluation of soil hydraulic property changes caused by surge water application. Soil Science Society of America Journal, 53(5), 1525-1530.

Scaloppi, E. G., Merkley, G. P., & Willardson, L. S. (1995). Intake parameters from advance and wetting phases of surface irrigation. Journal of Irrigation and Drainage Engineering, ASCE, 12(1), 57-70.

Schmitz, G. H., & Seus, J. G. (1992). Mathematical zero-inertia modelling of surface irrigation: Advance in furrows. Journal of Irrigation and Drainage Engineering, ASCE, 118(2), 1-18.

Schwankl, L. J., Raghuwanshi, N. S., & Wallender, W. W. (2000). Time series modelling for predicting spatially variable infiltration Journal of Irrigation and Drainage Engineering, ASCE, 126(5), 283-287.

Schwankl, L. J., Raghuwanshi, N. S., & Wallender, W. W. (2002). Furrow irrigation performance under spatially varying conditions. Journal of Irrigation and Drainage Engineering, ASCE, 126(6), 355-361

Schwankl, L. J., & Wallender, W. W. (1988). Zero inertia furrow modelling with variable infiltration and hydraulic characteristics. Trans of the ASAE, 31(5), 1470–1475.

Sepaskhah, A. R., & Afshar-Chamanabad, H. (2002). Determination of infiltration rate of every-other furrow irrigation. Biosystems Engineering, 82(4), 479-483.

Serralheiro, R. P. (1995). Furrow irrigation advance and infiltration equations for a Mediterranean soil. Journal of Agricultural Engineering Research, 62, 117-126.

Shafique, M. S., & Skogerboe, G. V. (1983). Impact of seasonal infiltration function variation on furrow irrigation performance. In: Advances in infiltration. Paper presented at the National Conference on Advances in Infiltration, 292-301.ASAE, St. Joseph, MI, USA.

Shepard, J. S., Wallender, W. W., & Hopmans, J. W. (1993). One-point method for estimating furrow infiltration. Trans of the ASAE, 36(2), 395-404.

Singer, M. J., & Munns, D. N. (1999). Soils: An introduction. Prentice-Hall. New York, 4th edition. ISBN 0136792421.

Singh, P., & Chauhan, H. S. (1972). Shape factors in irrigation water advance equation. Journal of Irrigation and Drainage Div., ASCE, 98(3), 443–458.

Singh, V. P. (1997). Kinematic wave modelling in water resources: environmental hydrology: New York, John Wiley & Sons.

Singh, V. P., & Ram, R. S. (1983). A kinematic model for surface irrigation. Verification by experimental data. Water Resources Research, 19(6), 1519-1612.

Sisson, J. B., & Wierenga, P. J. (1981). Spatial variability of steady state infiltration rate as a stochastic process. Soil Science Society of America Journal, 45, 699-704.

Smith, D. L., & Duke, H. R. (1984). Prediction of irrigation advance rates in real time. Paper presented at the American Society of Agricultural Engineers (ASAE) National Meeting. St. Joseph, Mich. Paper No. 84-2590.

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

Smith, R. J. (1988). Energy loss in branching flow and its application to irrigation pipeline design. Journal of Agricultural Engineering Research, 41(3), 181-189.

Smith, R. J. (1990). The Distribution of water from rigid and lay flat gated pipe. Paper presented at the Conference of Australian Society of Sugar Cane Technologists.

Smith, R. J. (1993). Infiltration parameters from irrigation advance data. Paper presented at the International Conference on Modelling and Simulation, University of Western Australia, Perth. 4, 1569-1574.

Smith, R. J. (2005). Study book: Irrigation science. University of Southern Queensland Toowoomba, QLD, Australia. 201-202.

Smith, R. J., Raine, S. R., & Minkovich, J. (2005). Irrigation application efficiency and deep drainage potential under surface irrigated cotton. Agricultural Water Management, 71(2), 117-130.

Strelkoff, T. S., & Clemens, A. J. (2003). Software for the design and management of surface irrigation systems. Retrieved 15 June, 2004, from http://www.uswcl.ars.ag.gov/publicat/index/ifm8.htm

Strelkoff, T. S., & Katoppodes, N. D. (1977). Border irrigation hydraulics with zero inertia. Journal of Irrigation and Drainage ASCE, 103(IR3), 325-338.

Tarboton, K. C., & Wallender, W. W. (1989). Field–wide furrow infiltration variability. Trans of the ASAE 32(3), 913-918.

Trout, T. J. (1990). Furrow inflow and infiltration variability impacts on irrigation management. Trans of the ASAE 33(4), 1171-1178.

Trout, T. J. (1992). Flow velocity and wetted perimeter effects on furrow infiltration. Trans of the ASAE 35(3), 855-863.

Trout, T. J., & Mackey, B. E. (1988). Furrow inflow and infiltration variability. Transactions of the ASAE, 31(2), 531-537.

Upadhyaya, S. K., & Raghuwanshi, N. S. (1999). Semiempirical infiltration equations for furrow irrigation systems. Journal of irrigation and Drainage, 125(4), 173-178.

USDA. (1997). SRFR v3. US Department of Agriculture, Agricultural Research Service, US Water Conservation Laboratory, Phoenix, AZ.

USDA. (1998). Infiltration, soil quality information sheet. Natural Resources Conservation Service. Retrieved 15 July 2004, from http://www.usda.gov

Valiantzas, J. D., Aggelides, S., & Sassalou, A. (2001). Furrow infiltration estimation from time to a single advance point. Agricultural Water Management, 52, 17-32.

Van Es, H. M., Odgen, C. B., Hill, R. L., Schendelbeck, R. R., & Tsegaye, T. (1999). Integrated assessment of space, time, and management-related variability of soil hydraulic properties. Soil Science Society of America Journal, 63(6), 1599-1606.

Voorhees, W. B., & Lindstrom, M. J. (1984). Long-term effects of tillage on soil tilth independent of wheel traffic compaction. Journal of Soil Science Society of America, 48, 152-156.

Walker, W. R. (2001). SIRMOD II - Surface irrigation simulation, evaluation and design: User's Guide and Technical Documentation. Utah State University, Logan, Utah.

Walker, W. R., & Busman, J. D. (1990). Real-time estimation of furrow infiltration. Journal of Irrigation and Drainage Engineering, 116(3), 299-318.

Walker, W. R., & Humpherys, A. S. (1983). Kinematic wave furrow irrigation model. Journal of Irrigation and Drainage Engineering, 109(4), 377-392.

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

Wallender, W. W. (1987). Furrow model with spatially varying infiltration. Paper presented at the American Society of Agricutural Engineers (ASAE) Annual Meeting Paper No. 84-2590, St. Joseph, Mich.

Warrick, A. W., & Hussein, A. A. (1993). Scaling of Richards equation for infiltration and drainage. Soil Science Society of America Journal, 57, 15-18.

Warrick, A. W., Lomen, D. O., & S R Yates. (1985). A generalised solution to infiltration. Soil Science Society of America Journal, 49, 34-38.

Wilke, O., & Smerdon, E. T. (1965). A solution of the irrigation advance problem. Journal of  Irrigation and Drainage Div., ASCE, 19(3), 23–24.

Wu, L., & Pan, L. (1997). A generalised solution to infiltration from single ring infiltrometers by scaling. Soil Science Society of America Journal, 61, 1318-1322.

Youngs, E. G., & Price, R. I. (1981). Scaling of infiltration behaviour in dissimilar porous materials. Water Resources Research, 17, 1065-1070.

# APPENDIX A: Advance Data and Spread Sheet Programmes for the Different Soils Analysed Under Chapter 5.

**Table A.1 Showing the advance data and cumulative infiltration given by different methods for data set D1.**

| | | | | | |
|---|---|---|---|---|---|
| **Constants** | | | | | |
| | | | | | |
| Cross sectional area | 0.038 | $m^2$ | | | |
| Discharge / inflow *Q* | 0.2664 | $m^3$/min | | | |
| Slope | Not given | % | | | |
| Furrow Length | 750 | m | | | |
| Run off | Not given | $m^3$/min | | | |
| Del y | 0.77 | | | | |
| | | | | | |
| **Data** | | | | | |
| | Distance | Advance time | | | |
| | *x* | *t* | | | |
| | (m) | (min) | | | |
| | 0 | 0 | | | |
| | 125 | 59 | | | |
| | 250 | 142 | | | |
| | 375 | 262 | | | |
| | 500 | 431 | | | |
| | 625 | 577 | | | |
| **Valiantzas method** | | | Calculating alpha | Alpha | Alpha(new) |
| | *alpha* | 0.786 | | 0.8 | 0.800 |
| | | | | 0.79 | 0.790 |
| | *R* | 0.36037 | | 0.78 | 0.780 |
| | | | | 0.77 | 0.770 |
| | *Del z* | 0.76683 | | 0.76 | 0.760 |
| | | | | 0.786 | 0.786 |
| | *k* | 0.00183 | | | |
| | | | | | |
| | *F(alpha)* | -0.00171 | | | |
| | | | | | |
| | *dk / d(alpha)* | 0.02945 | | | |
| | | | | | |
| | *F'(alpha)* | 4.66438 | | | |
| | | | | | |
| | *alpha(new)* | 0.78637 | | | |
| | | | | | |
| | *I* | 0.27884 | $m^3$/m | | |

| | | |
|---|---|---|
| **INFILT** | *r* | 0.66918 |
| | *a* | 0.35779 |
| | *fo* | 0.00005 |
| | *k* | 0.02615 |
| | *del z* | 0.789 |

| | | | |
|---|---|---|---|
| **Two Point** | *r* | 0.647 | |
| | | | |
| | *fo* | 0 | $m^3$/min/m |
| | | | |
| | $V_L$ | 0.2167 | m^2 |
| | | | |
| | $V_{0.5L}$ | 0.1569 | m^2 |
| | | | |
| | *a* | 0.4092 | |
| | | | |
| | *del z* | 0.772 | |
| | | | |
| | *k* | 0.02082 | |

| | | | |
|---|---|---|---|
| **Shepard** | *A* | 0.000152 | m^2/min |
| | | | |
| | *S* | 0.008383 | m/min^1/2 |
| | | | |
| | *I* | 0.2892 | m^3/min |
| | | | |
| | | | |
| **Raghuwanshi** | $X_{max}$ | 800.0 | m |
| | | | |
| | *Theta* | 0.0025685 | |
| | | | |
| | $f_o$ | 0.0003330 | m^3/min/m |
| | | | |
| | *F* | 0.171595 | |
| | | | |
| | *I* | 0.32475 | m^3/min |

| | | | |
|---|---|---|---|
| **Linear infiltration** | *r* | 0.6470 | |
| | | | |
| | *fo* | 0.0003128 | m^3/min/m |
| | | | |
| | *Zcr* | 0.10711 | m^3 |

| Time (min) | Cumulative Infiltration ($m^3$/ m) | | | | | |
|---|---|---|---|---|---|---|
| | Two Point | INFILT | Shepard | Raghuwanshi | Valiantzas | Linear |
| 0 | 0.0000 | 0.0000 | 0.000000 | 0 | 0.00700 | 0.10711 |
| 5 | 0.0402 | 0.0468 | 0.019507 | 0.0038544 | 0.01350 | 0.10868 |
| 10 | 0.0534 | 0.0601 | 0.028032 | 0.0076808 | 0.01820 | 0.11024 |
| 20 | 0.0709 | 0.0774 | 0.040534 | 0.0152512 | 0.02632 | 0.11337 |
| 40 | 0.0942 | 0.0999 | 0.059107 | 0.0300723 | 0.04033 | 0.11962 |
| 60 | 0.1112 | 0.1162 | 0.074065 | 0.0444848 | 0.05285 | 0.12588 |
| 80 | 0.1251 | 0.1294 | 0.087154 | 0.0585092 | 0.06448 | 0.13213 |
| 100 | 0.1370 | 0.1408 | 0.099047 | 0.0721648 | 0.07551 | 0.13839 |
| 120 | 0.1476 | 0.1510 | 0.110091 | 0.0854702 | 0.08607 | 0.14464 |
| 140 | 0.1573 | 0.1602 | 0.120492 | 0.0984429 | 0.09626 | 0.15090 |
| 160 | 0.1661 | 0.1687 | 0.130384 | 0.1110995 | 0.10614 | 0.15715 |
| 180 | 0.1743 | 0.1766 | 0.139859 | 0.1234559 | 0.11576 | 0.16341 |
| 200 | 0.1820 | 0.1841 | 0.148986 | 0.135527 | 0.12516 | 0.16966 |
| 240 | 0.1961 | 0.1978 | 0.166387 | 0.1588702 | 0.14338 | 0.18217 |
| 260 | 0.2026 | 0.2042 | 0.174733 | 0.1701687 | 0.15223 | 0.18843 |
| 280 | 0.2088 | 0.2104 | 0.182878 | 0.1812349 | 0.16095 | 0.19468 |
| 300 | 0.2148 | 0.2163 | 0.190844 | 0.1920805 | 0.16953 | 0.20094 |
| 340 | 0.2261 | 0.2275 | 0.206307 | 0.2131535 | 0.18634 | 0.21345 |
| 380 | 0.2366 | 0.2380 | 0.221233 | 0.2334696 | 0.20274 | 0.22596 |
| 420 | 0.2465 | 0.2480 | 0.235704 | 0.2531027 | 0.21876 | 0.23847 |
| 460 | 0.2559 | 0.2575 | 0.249784 | 0.2721194 | 0.23447 | 0.25098 |
| 500 | 0.2647 | 0.2666 | 0.263524 | 0.29058 | 0.24988 | 0.26349 |
| 540 | 0.2732 | 0.2754 | 0.276964 | 0.3085388 | 0.26504 | 0.27600 |
| 580 | 0.2813 | 0.2838 | 0.290135 | 0.3260447 | 0.27995 | 0.28851 |
| 620 | 0.2891 | 0.2920 | 0.303067 | 0.3431419 | 0.29465 | 0.30102 |
| 635 | 0.2919 | 0.2949 | 0.307859 | 0.3494563 | 0.30011 | 0.30571 |

**Table A.2 Advance trajectories given by different methods for data set D1.**

| Time min) | Advance Distance (m) | | | | | |
|---|---|---|---|---|---|---|
| | Two Point | INFILT | Shepard | Raghu | Valiant | Linear |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 22 | 20 | 30 | 24.02 | 32 | 10 |
| 10 | 38 | 35 | 52 | 46.63 | 59 | 19 |
| 20 | 63 | 59 | 88 | 88.13 | 104 | 38 |
| 40 | 105 | 99 | 142 | 158.76 | 172 | 74 |
| 60 | 139 | 133 | 185 | 216.65 | 224 | 108 |
| 80 | 169 | 163 | 221 | 264.94 | 265 | 141 |
| 100 | 197 | 191 | 253 | 305.86 | 300 | 171 |
| 120 | 223 | 217 | 282 | 340.96 | 330 | 201 |
| 140 | 248 | 242 | 307 | 371.40 | 356 | 229 |
| 160 | 271 | 265 | 331 | 398.06 | 380 | 256 |
| 180 | 293 | 287 | 353 | 421.60 | 401 | 281 |
| 200 | 314 | 309 | 373 | 442.53 | 420 | 306 |
| 240 | 354 | 349 | 411 | 478.14 | 454 | 351 |
| 260 | 373 | 369 | 428 | 493.41 | 469 | 373 |
| 280 | 392 | 387 | 444 | 507.29 | 483 | 394 |
| 300 | 410 | 406 | 460 | 519.98 | 497 | 413 |
| 340 | 444 | 441 | 489 | 542.31 | 521 | 451 |
| 380 | 478 | 474 | 516 | 561.34 | 543 | 485 |
| 420 | 510 | 507 | 541 | 577.76 | 563 | 518 |
| 460 | 540 | 537 | 564 | 592.06 | 582 | 548 |
| 500 | 570 | 567 | 586 | 604.63 | 599 | 576 |
| 540 | 599 | 596 | 607 | 615.77 | 614 | 602 |
| 580 | 627 | 624 | 626 | 625.71 | 629 | 627 |
| 620 | 654 | 651 | 645 | 634.63 | 643 | 650 |
| 625 | 658 | 655 | 647 | 635.68 | 645 | 653 |

**Table A.3 Advance data and cumulative infiltration given by different methods for data set D2.**

| | | | | | |
|---|---|---|---|---|---|
| **Constants** | | | | | |
| | | | | | |
| Cross sectional area | 0.038 | m^2 | | | |
| Discharge / inflow *Q* | 0.3 | m^3/min | | | |
| Slope | Not given | % | | | |
| Furrow Length | 300 | m | | | |
| Run off | Not given | m^3/min | | | |
| Del y | 0.77 | | | | |
| | | | | | |
| **Data** | | | | | |
| | Distance | Advance Time | | | |
| | *x* | *t* | | | |
| | (m) | (min) | | | |
| | 0 | 0 | | | |
| | 60 | 30 | | | |
| | 180 | 170 | | | |
| | 240 | 277 | | | |
| **Valiantzas method** | | | Calculating alpha | Alpha | Alpha(new) |
| | *alpha* | 0.819 | | 0.8 | 0.800 |
| | | | | 0.79 | 0.790 |
| | *R* | 0.29207 | | 0.78 | 0.780 |
| | | | | 0.77 | 0.770 |
| | *Del z* | 0.79645 | | 0.76 | 0.760 |
| | | | | 0.819 | 0.819 |
| | *k* | 0.00388 | | | |
| | | | | | |
| | *F(alpha)* | -0.00041 | | | |
| | | | | | |
| | *dk / d(alpha)* | 0.11836 | | | |
| | | | | | |
| | *F'(alpha)* | 11.17620 | | | |
| | | | | | |
| | *alpha(new)* | 0.81904 | | | |
| | | | | | |
| | *I* | 0.39579 | m^3/m | | |

| | | |
|---|---|---|
| **INFILT** | *r* | 0.61696 |
| | *a* | 0.39465 |
| | *fo* | 0.00021 |
| | *k* | 0.03901 |
| | *del z* | 0.784 |

| | | | |
|---|---|---|---|
| **Two Point** | *r* | 0.589 | |
| | | | |
| | *fo* | 0 | m^3/min/m |
| | | | |
| | *V L* | 0.3170 | m^2 |
| | | | |
| | *V 0.5L* | 0.2541 | m^2 |
| | | | |
| | *a* | 0.4532 | |
| | | | |
| | *del z* | 0.769 | |
| | | | |
| | *k* | 0.03224 | |

| | | | |
|---|---|---|---|
| **Shepard** | *A* | 0.000317 | m^2/min |
| | | | |
| | *S* | 0.019773 | m/min^1/2 |
| | | | |
| | *I* | 0.4169 | m^3/min |
| | | | |
| | | | |
| **Raghuwanshi** | *Xmax* | 335.0 | m |
| | | | |
| | *Theta* | 0.0052206 | |
| | *f o* | 0.0008955 | m^3/min/m |
| | | | |
| | *F* | 0.332746 | |
| | | | |
| | *I* | 0.50245 | m^3/min |

| | | | |
|---|---|---|---|
| **Linear Infiltration** | *r* | 0.5892 | |
| | | | |
| | *fo* | 0.0009345 | m^3/min/m |
| | | | |
| | *Zcr* | 0.15411 | m^3 |

| Time (min) | Cumulative Infiltration ($m^3/m$) | | | | | |
|---|---|---|---|---|---|---|
| | Two Point | INFIL | Shepard | Raghu | Valiant | Linear |
| 0 | 0.000 | 0.00 | 0.000000 | 0 | 0.00700 | 0.15411 |
| 5 | 0.067 | 0.07 | 0.045799 | 0.01305 | 0.02151 | 0.15878 |
| 10 | 0.092 | 0.10 | 0.065698 | 0.0258792 | 0.03260 | 0.16346 |
| 20 | 0.125 | 0.13 | 0.094767 | 0.0508977 | 0.05217 | 0.17280 |
| 40 | 0.172 | 0.18 | 0.137733 | 0.0985252 | 0.08668 | 0.19149 |
| 60 | 0.206 | 0.21 | 0.172177 | 0.1432066 | 0.11807 | 0.21018 |
| 80 | 0.235 | 0.24 | 0.202210 | 0.185234 | 0.14758 | 0.22887 |
| 100 | 0.260 | 0.26 | 0.229423 | 0.2248706 | 0.17577 | 0.24756 |
| 120 | 0.282 | 0.28 | 0.254634 | 0.2623533 | 0.20295 | 0.26625 |
| 140 | 0.303 | 0.30 | 0.278327 | 0.2978957 | 0.22932 | 0.28494 |
| 160 | 0.322 | 0.32 | 0.300819 | 0.3316901 | 0.25502 | 0.30363 |
| 180 | 0.339 | 0.34 | 0.322329 | 0.3639098 | 0.28014 | 0.32232 |
| 200 | 0.356 | 0.36 | 0.343017 | 0.394711 | 0.30475 | 0.34101 |
| 240 | 0.386 | 0.39 | 0.382382 | 0.4526062 | 0.35271 | 0.37839 |
| 260 | 0.401 | 0.40 | 0.401229 | 0.479941 | 0.37613 | 0.39708 |
| 277 | 0.412 | 0.42 | 0.416874 | 0.5024373 | 0.39579 | 0.41297 |

**Table A.4 Advance trajectories given by different methods for data set D2.**

| Time (min) | Advance Distance (m) | | | | | |
|---|---|---|---|---|---|---|
| | Two Point | INFIL | Shepard | Raghu | Valiant | Linear |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 19 | 17 | 23 | 14.61 | 31 | 8 |
| 10 | 30 | 28 | 37 | 28.00 | 53 | 16 |
| 20 | 48 | 46 | 58 | 51.68 | 83 | 31 |
| 40 | 74 | 72 | 88 | 89.54 | 120 | 58 |
| 60 | 96 | 94 | 111 | 118.48 | 144 | 82 |
| 80 | 114 | 113 | 130 | 141.32 | 162 | 104 |
| 100 | 131 | 130 | 146 | 159.79 | 176 | 124 |
| 120 | 146 | 146 | 160 | 175.05 | 187 | 142 |
| 140 | 160 | 160 | 173 | 187.87 | 197 | 158 |
| 160 | 174 | 173 | 185 | 198.78 | 205 | 173 |
| 180 | 186 | 186 | 196 | 208.19 | 213 | 187 |
| 200 | 198 | 198 | 206 | 216.38 | 219 | 199 |
| 240 | 221 | 221 | 225 | 229.95 | 231 | 222 |
| 260 | 231 | 231 | 233 | 235.63 | 236 | 232 |
| 277 | 240 | 240 | 240 | 240.00 | 240 | 240 |

**Table A.5 Advance data and cumulative infiltration given by different methods for data set D3.**

| | | | |
|---|---|---|---|
| **Constants** | | | |
| | | | |
| Cross sectional area | | 0.03 | m^2 |
| Discharge / inflow *Q* | | 0.121 | m^3/min |
| Slope | | Not given | % |
| Furrow Length | | 1200 | m |
| Cut-off Time | | 2790 | min |
| Run off | | 0.0858 | m^3/min |
| Del y | | 0.77 | |
| | | | |
| **Data** | | | |
| | Distance | Advance time | |
| | *x* | *t* | |
| | (m) | (min) | |
| | 0 | 0 | |
| | 200 | 336 | |
| | 600 | 826 | |
| | 800 | 1185 | |
| | 1000 | 1934 | |
| | 1200 | 2523 | |
| **Valiantzas** | | | |
| | *alpha* | 0.727 | |
| | | | |
| | *R* | 0.38071 | |
| | | | |
| | *Del z* | 0.76785 | |
| | | | |
| | *k* | 0.00099 | |
| | | | |
| | *F(alpha)* | 0.00087 | |
| | | | |
| | *dk / d(alpha)* | 0.00748 | |
| | | | |
| | *F'(alpha)* | 3.47219 | |
| | | | |
| | *alpha(new)* | 0.72675 | |
| | | | |
| | *I* | 0.29968 | m^3/m |

| | | |
|---|---|---|
| **INFILT** | *r* | 0.70922 |
| | *a* | 0 |
| | *fo* | 0.00008 |
| | *k* | 0.11539 |
| | *del z* | 1.000 |

| | | | |
|---|---|---|---|
| **Two Point** | *r* | 0.537 | |
| | | | |
| | *fo* | 2.93333E-05 | m^3/min/m |
| | | | |
| | *V L* | 0.1831 | m^2 |
| | | | |
| | *V 0.5L* | 0.1335 | m^2 |
| | | | |
| | *a* | 0.4182 | |
| | | | |
| | *del z* | 0.794 | |
| | | | |
| | *k* | 0.00871 | |

| | | | |
|---|---|---|---|
| **Shepard** | *A* | 0.000027 | m^2/min |
| | | | |
| | *S* | 0.004692 | m/min^1/2 |
| | | | |
| | *I* | 0.3050 | m^3/min |
| | | | |
| | | | |
| **Raghuwanshi** | *Xmax* | 1350.0 | m |
| | | | |
| | *Theta* | 0.0007031 | |
| | | | |
| | *f o* | 0.0000896 | m^3/min/m |
| | | | |
| | *F* | 0.134119 | |
| | | | |
| | *I* | 0.33750 | m^3/min |

| | | | |
|---|---|---|---|
| **Linear Infil** | *r* | 0.5365 | |
| | | | |
| | *fo* | 0.0000863 | m^3/min/m |
| | | | |
| | *Zcr* | 0.08956 | m^3 |

| Time (min) | Cumulative Infiltration m³/ m | | | | | |
|---|---|---|---|---|---|---|
| | Two Point | Infil | Shepard | Raghu | Valiant | Linear |
| 0 | 0.0000 | 0.0000 | 0.000000 | 0 | 0.00700 | 0.08956 |
| 5 | 0.0172 | 0.1158 | 0.010629 | 0.0009188 | 0.01018 | 0.08999 |
| 10 | 0.0231 | 0.1162 | 0.015112 | 0.0018359 | 0.01226 | 0.09042 |
| 20 | 0.0311 | 0.1170 | 0.021533 | 0.0036652 | 0.01570 | 0.09128 |
| 40 | 0.0419 | 0.1186 | 0.030774 | 0.0073042 | 0.02140 | 0.09301 |
| 60 | 0.0500 | 0.1202 | 0.037993 | 0.0109174 | 0.02633 | 0.09474 |
| 80 | 0.0568 | 0.1218 | 0.044164 | 0.0145052 | 0.03083 | 0.09646 |
| 100 | 0.0627 | 0.1234 | 0.049667 | 0.0180679 | 0.03502 | 0.09819 |
| 120 | 0.0680 | 0.1250 | 0.054695 | 0.021606 | 0.03900 | 0.09991 |
| 140 | 0.0729 | 0.1266 | 0.059363 | 0.0251196 | 0.04279 | 0.10164 |
| 160 | 0.0775 | 0.1282 | 0.063745 | 0.0286093 | 0.04644 | 0.10337 |
| 180 | 0.0817 | 0.1298 | 0.067895 | 0.0320752 | 0.04996 | 0.10509 |
| 200 | 0.0858 | 0.1314 | 0.071849 | 0.0355178 | 0.05338 | 0.10682 |
| 240 | 0.0933 | 0.1346 | 0.079281 | 0.0423341 | 0.05995 | 0.11027 |
| 260 | 0.0968 | 0.1362 | 0.082799 | 0.0457085 | 0.06312 | 0.11200 |
| 280 | 0.1002 | 0.1378 | 0.086204 | 0.0490609 | 0.06623 | 0.11373 |
| 300 | 0.1035 | 0.1394 | 0.089509 | 0.0523914 | 0.06927 | 0.11545 |
| 340 | 0.1097 | 0.1426 | 0.095856 | 0.0589884 | 0.07520 | 0.11891 |
| 380 | 0.1156 | 0.1458 | 0.101903 | 0.0655019 | 0.08094 | 0.12236 |
| 420 | 0.1213 | 0.1490 | 0.107695 | 0.0719342 | 0.08652 | 0.12581 |
| 460 | 0.1267 | 0.1522 | 0.113268 | 0.0782875 | 0.09196 | 0.12927 |
| 500 | 0.1319 | 0.1554 | 0.118651 | 0.0845641 | 0.09727 | 0.13272 |
| 540 | 0.1369 | 0.1586 | 0.123866 | 0.0907661 | 0.10246 | 0.13617 |
| 580 | 0.1417 | 0.1618 | 0.128931 | 0.0968955 | 0.10755 | 0.13962 |
| 620 | 0.1464 | 0.1650 | 0.133861 | 0.1029543 | 0.11254 | 0.14308 |
| 720 | 0.1576 | 0.1730 | 0.145678 | 0.1178055 | 0.12465 | 0.15171 |
| 820 | 0.1682 | 0.1810 | 0.156883 | 0.1322569 | 0.13632 | 0.16034 |
| 920 | 0.1782 | 0.1890 | 0.167587 | 0.1463357 | 0.14760 | 0.16898 |
| 1020 | 0.1878 | 0.1970 | 0.177869 | 0.1600673 | 0.15855 | 0.17761 |
| 1120 | 0.1971 | 0.2050 | 0.187790 | 0.1734751 | 0.16920 | 0.18624 |
| 1220 | 0.2060 | 0.2130 | 0.197397 | 0.1865811 | 0.17961 | 0.19487 |
| 1320 | 0.2146 | 0.2210 | 0.206728 | 0.1994059 | 0.18978 | 0.20351 |
| 1420 | 0.2230 | 0.2290 | 0.215814 | 0.2119685 | 0.19974 | 0.21214 |
| 1520 | 0.2312 | 0.2370 | 0.224681 | 0.2242868 | 0.20951 | 0.22077 |
| 1620 | 0.2391 | 0.2450 | 0.233349 | 0.2363773 | 0.21911 | 0.22940 |
| 1720 | 0.2469 | 0.2530 | 0.241837 | 0.2482554 | 0.22855 | 0.23804 |
| 1820 | 0.2546 | 0.2610 | 0.250161 | 0.2599356 | 0.23783 | 0.24667 |
| 1920 | 0.2621 | 0.2690 | 0.258333 | 0.2714314 | 0.24698 | 0.25530 |
| 2220 | 0.2837 | 0.2930 | 0.282053 | 0.304933 | 0.27369 | 0.28120 |
| 2523 | 0.3046 | 0.3172 | 0.304980 | 0.3374941 | 0.29968 | 0.30736 |

**Table A.6 Advance trajectories given by different methods for data set D3.**

| Time (min) | Advance Distance (m) | | | | | |
|---|---|---|---|---|---|---|
| | Two Point | INFILT | Shepard | Raghu | Valiant | Linear |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 16 | 4 | 19 | 21.07 | 19 | 5 |
| 10 | 29 | 9 | 35 | 41.49 | 35 | 11 |
| 20 | 51 | 17 | 61 | 80.51 | 66 | 21 |
| 40 | 86 | 34 | 103 | 151.95 | 118 | 42 |
| 60 | 116 | 51 | 138 | 215.78 | 162 | 63 |
| 80 | 143 | 68 | 168 | 273.16 | 200 | 83 |
| 100 | 167 | 85 | 196 | 325.01 | 234 | 102 |
| 120 | 189 | 101 | 221 | 372.09 | 266 | 122 |
| 140 | 211 | 117 | 245 | 415.04 | 294 | 141 |
| 160 | 231 | 133 | 267 | 454.38 | 321 | 159 |
| 180 | 250 | 148 | 287 | 490.54 | 345 | 177 |
| 200 | 268 | 164 | 307 | 523.89 | 368 | 195 |
| 240 | 302 | 194 | 343 | 583.39 | 410 | 230 |
| 260 | 318 | 209 | 360 | 610.04 | 430 | 247 |
| 280 | 334 | 223 | 377 | 634.89 | 448 | 264 |
| 300 | 349 | 238 | 393 | 658.14 | 466 | 280 |
| 340 | 378 | 266 | 423 | 700.36 | 499 | 312 |
| 380 | 406 | 294 | 451 | 737.73 | 529 | 343 |
| 420 | 432 | 321 | 478 | 771.04 | 557 | 373 |
| 460 | 457 | 348 | 503 | 800.90 | 584 | 402 |
| 500 | 481 | 374 | 528 | 827.84 | 609 | 430 |
| 540 | 504 | 399 | 551 | 852.26 | 632 | 457 |
| 580 | 527 | 424 | 573 | 874.49 | 654 | 483 |
| 620 | 549 | 448 | 594 | 894.83 | 675 | 509 |
| 720 | 600 | 506 | 645 | 938.79 | 723 | 569 |
| 820 | 648 | 561 | 691 | 975.01 | 767 | 625 |
| 920 | 692 | 613 | 734 | 1005.36 | 806 | 677 |
| 1020 | 735 | 663 | 774 | 1031.17 | 843 | 726 |
| 1120 | 775 | 710 | 812 | 1053.38 | 876 | 772 |
| 1220 | 813 | 755 | 848 | 1072.70 | 908 | 815 |
| 1320 | 850 | 798 | 882 | 1089.66 | 937 | 855 |
| 1420 | 885 | 838 | 914 | 1104.66 | 965 | 893 |
| 1520 | 918 | 877 | 945 | 1118.03 | 991 | 929 |
| 1620 | 951 | 915 | 975 | 1130.01 | 1016 | 962 |
| 1720 | 982 | 950 | 1003 | 1140.82 | 1039 | 994 |
| 1820 | 1012 | 985 | 1031 | 1150.62 | 1062 | 1025 |
| 1920 | 1041 | 1017 | 1057 | 1159.54 | 1084 | 1053 |
| 2220 | 1124 | 1108 | 1132 | 1182.07 | 1144 | 1132 |
| 2523 | 1200 | 1190 | 1200 | 1200.00 | 1198 | 1200 |

**Table A.7 Advance data and cumulative infiltration given by different methods for data set D4.**

| | | | | | |
|---|---|---|---|---|---|
| **Constants** | | | | | |
| | | | | | |
| Cross sectional area | 0.03 | m^2 | | | |
| Discharge / inflow *Q* | 0.07758 | m^3/min | | | |
| Slope | 0.1 | % | | | |
| Moisture Depletion | 60 | mm | | | |
| Cut-off Time | 1446 | min | | | |
| Run off | 0.0687 | m^3/min | | | |
| Del y | 0.77 | | | | |
| | | | | | |
| **Data** | | | | | |
| | Distance | Advance Time | | | |
| | *x* | *t* | | | |
| | (m) | (min) | | | |
| | 0 | 0 | | | |
| | 20 | 7 | | | |
| | 300 | 150 | | | |
| | 600 | 496 | | | |
| | 800 | 735 | | | |
| **Valiantzas method** | | | Calculating alpha | Alpha | Alpha(new) |
| | *alpha* | 0.676 | | 0.8 | 0.800 |
| | | | | 0.79 | 0.790 |
| | *R* | 0.64871 | | 0.78 | 0.780 |
| | | | | 0.77 | 0.770 |
| | *Del z* | 0.68260 | | 0.76 | 0.760 |
| | | | | 0.676 | 0.676 |
| | *k* | 0.00070 | | | |
| | | | | | |
| | *F(alpha)* | 0.00003 | | | |
| | | | | | |
| | *dk / d(alpha)* | 0.00437 | | | |
| | | | | | |
| | *F'(alpha)* | 0.53021 | | | |
| | | | | | |
| | *alpha(new)* | 0.67595 | | | |
| | | | | | |
| | *I* | 0.06734 | m^3/m | | |

| | | |
|---|---|---|
| **INFILT** | *r* | 0.63693 |
| | *a* | 0.43195 |
| | *fo* | 0 |
| | *k* | 0.00481 |
| | *del z* | 0.701 |

| | | | |
|---|---|---|---|
| **Two Point** | *r* | 0.617 | |
| | | | |
| | *fo* | 0.0000111 | m^3/min/m |
| | | | |
| | *V L* | 0.0431 | m^2 |
| | | | |
| | *V 0.5L* | 0.0147 | m^2 |
| | | | |
| | *a* | 0.6790 | |
| | | | |
| | *del z* | 0.691 | |
| | | | |
| | *k* | 0.00071 | |

| | | | |
|---|---|---|---|
| **Shepard** | *A* | 0.000094 | m^2/min |
| | | | |
| | *S* | 0.000093 | m/min^1/2 |
| | | | |
| | *I* | 0.0718 | m^3/min |
| | | | |
| | | | |
| **Raghuwanshi** | *Xmax* | 1025.0 | m |
| | | | |
| | *Theta* | 0.0022404 | |
| | | | |
| | *f o* | 0.0000757 | m^3/min/m |
| | | | |
| | *F* | 0.019900 | |
| | | | |
| | *I* | 0.07170 | m^3/min |

| | | | |
|---|---|---|---|
| **Linear Infil** | *r* | 0.6172 | |
| | | | |
| | *fo* | 0.0000898 | m^3/min/m |
| | | | |
| | *Zcr* | 0.00736 | m^3 |

| Time (min) | Cumulative Infiltration m³/ m | | | | | |
|---|---|---|---|---|---|---|
| | Two Point | Infil | Shepard | Raghu | Valiant | Linear |
| 0 | 0.0000 | 0.0000 | 0.000000 | 0 | 0.00700 | 0.00736 |
| 5 | 0.0022 | 0.0031 | 0.000679 | 0.0006001 | 0.00907 | 0.00781 |
| 10 | 0.0035 | 0.0048 | 0.001236 | 0.0011977 | 0.01030 | 0.00826 |
| 20 | 0.0056 | 0.0074 | 0.002301 | 0.0023856 | 0.01228 | 0.00916 |
| 40 | 0.0091 | 0.0115 | 0.004359 | 0.0047331 | 0.01543 | 0.01095 |
| 60 | 0.0120 | 0.0148 | 0.006376 | 0.007044 | 0.01809 | 0.01275 |
| 80 | 0.0147 | 0.0177 | 0.008373 | 0.00932 | 0.02048 | 0.01454 |
| 100 | 0.0172 | 0.0203 | 0.010357 | 0.0115626 | 0.02267 | 0.01634 |
| 120 | 0.0196 | 0.0227 | 0.012331 | 0.0137732 | 0.02472 | 0.01814 |
| 140 | 0.0218 | 0.0250 | 0.014298 | 0.0159533 | 0.02667 | 0.01993 |
| 160 | 0.0239 | 0.0272 | 0.016260 | 0.0181043 | 0.02853 | 0.02173 |
| 180 | 0.0260 | 0.0293 | 0.018217 | 0.0202273 | 0.03031 | 0.02353 |
| 200 | 0.0280 | 0.0313 | 0.020170 | 0.0223236 | 0.03203 | 0.02532 |
| 240 | 0.0318 | 0.0350 | 0.024067 | 0.0264408 | 0.03532 | 0.02891 |
| 260 | 0.0337 | 0.0368 | 0.026011 | 0.0284638 | 0.03689 | 0.03071 |
| 280 | 0.0355 | 0.0386 | 0.027953 | 0.0304645 | 0.03843 | 0.03251 |
| 300 | 0.0373 | 0.0403 | 0.029894 | 0.0324439 | 0.03993 | 0.03430 |
| 340 | 0.0407 | 0.0435 | 0.033769 | 0.0363424 | 0.04283 | 0.03789 |
| 380 | 0.0441 | 0.0467 | 0.037638 | 0.0401663 | 0.04563 | 0.04149 |
| 420 | 0.0473 | 0.0497 | 0.041502 | 0.0439218 | 0.04834 | 0.04508 |
| 460 | 0.0505 | 0.0526 | 0.045362 | 0.047615 | 0.05096 | 0.04867 |
| 500 | 0.0536 | 0.0554 | 0.049219 | 0.0512511 | 0.05351 | 0.05226 |
| 540 | 0.0566 | 0.0581 | 0.053071 | 0.0548351 | 0.05599 | 0.05586 |
| 580 | 0.0596 | 0.0608 | 0.056921 | 0.0583714 | 0.05842 | 0.05945 |
| 620 | 0.0625 | 0.0633 | 0.060769 | 0.061864 | 0.06079 | 0.06304 |
| 680 | 0.0667 | 0.0671 | 0.066535 | 0.0670294 | 0.06425 | 0.06843 |
| 735 | 0.0705 | 0.0704 | 0.071817 | 0.0716951 | 0.06734 | 0.07337 |

**Table A.8 Advance trajectories given by different methods for data set D4.**

| Time (min) | Advance Distance (m) | | | | | |
|---|---|---|---|---|---|---|
| | Two Point | INFILT | Shepard | Raghu | Valiant | Linear |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 16 | 15 | 16 | 24.21 | 12 | 13 |
| 10 | 30 | 29 | 32 | 47.30 | 24 | 25 |
| 20 | 58 | 55 | 63 | 90.42 | 46 | 49 |
| 40 | 106 | 100 | 119 | 166.18 | 87 | 95 |
| 60 | 148 | 139 | 170 | 230.58 | 124 | 138 |
| 80 | 187 | 175 | 216 | 285.99 | 158 | 178 |
| 100 | 222 | 208 | 258 | 334.18 | 190 | 215 |
| 120 | 255 | 238 | 296 | 376.47 | 221 | 251 |
| 140 | 285 | 267 | 332 | 413.88 | 250 | 284 |
| 160 | 314 | 294 | 364 | 447.21 | 277 | 315 |
| 180 | 341 | 320 | 395 | 477.09 | 303 | 345 |
| 200 | 367 | 345 | 423 | 504.03 | 329 | 373 |
| 240 | 415 | 391 | 474 | 550.68 | 377 | 425 |
| 260 | 437 | 412 | 497 | 571.01 | 399 | 449 |
| 280 | 458 | 433 | 518 | 589.66 | 421 | 472 |
| 300 | 479 | 453 | 539 | 606.85 | 443 | 494 |
| 340 | 517 | 492 | 576 | 637.44 | 483 | 535 |
| 380 | 553 | 528 | 609 | 663.86 | 522 | 572 |
| 420 | 587 | 562 | 639 | 686.91 | 559 | 606 |
| 460 | 619 | 595 | 666 | 707.19 | 594 | 637 |
| 500 | 649 | 626 | 691 | 725.18 | 627 | 666 |
| 540 | 678 | 656 | 713 | 741.24 | 659 | 693 |
| 580 | 705 | 685 | 734 | 755.67 | 690 | 718 |
| 620 | 731 | 713 | 753 | 768.70 | 720 | 741 |
| 680 | 768 | 752 | 779 | 786.04 | 763 | 773 |
| 735 | 800 | 787 | 800 | 800.00 | 800 | 800 |

**Table A.9 Advance data and cumulative infiltration given by different methods for data set D5.**

| | | | | | |
|---|---|---|---|---|---|
| **Constants** | | | | | |
| | | | | | |
| Cross sectional area | 0.038 | m^2 | | | |
| Discharge /In Flow *Q* | 0.4603 | m^3/min | | | |
| Slope | Not given | % | | | |
| Furrow Length | 750 | m | | | |
| Run off | Not given | m^3/min | | | |
| Del y | 0.77 | | | | |
| | | | | | |
| **Data** | | | | | |
| | Distance | Advance Time | | | |
| | *x* | *t* | | | |
| | (m) | (min) | | | |
| | 0 | 0 | | | |
| | 150 | 61 | | | |
| | 300 | 121 | | | |
| | 450 | 217 | | | |
| | 600 | 325 | | | |
| | 750 | 441 | | | |
| **Valiantzas method** | | | Calculating alpha | Alpha | Alpha(new) |
| | *alpha* | 0.799 | | 0.8 | 0.800 |
| | | | | 0.79 | 0.790 |
| | *R* | 0.33735 | | 0.78 | 0.780 |
| | | | | 0.77 | 0.770 |
| | *Del z* | 0.77593 | | 0.76 | 0.760 |
| | | | | 0.799 | 0.799 |
| | *k* | 0.00233 | | | |
| | | | | | |
| | *F(alpha)* | -0.00019 | | | |
| | | | | | |
| | *dk / d(alpha)* | 0.04877 | | | |
| | | | | | |
| | *F'(alpha)* | 6.33371 | | | |
| | | | | | |
| | *alpha(new)* | 0.79903 | | | |
| | | | | | |
| | *I* | 0.30890 | m^3/m | | |

| | | |
|---|---|---|
| **INFILT** | *r* | 0.75715 |
| | *a* | 0.10675 |
| | *fo* | 0.000303 |
| | *k* | 0.09451 |
| | | |
| | *del z* | 0.917 |

| | | | |
|---|---|---|---|
| **Two Point** | *r* | 0.720 | |
| | | | |
| | *fo* | 0 | m^3/min/m |
| | | | |
| | *V L* | 0.2414 | m^2 |
| | | | |
| | *V 0.5L* | 0.1927 | m^2 |
| | | | |
| | *a* | 0.3177 | |
| | | | |
| | *del z* | 0.798 | |
| | | | |
| | *k* | 0.04371 | |

| | | | |
|---|---|---|---|
| **Shepard** | *A* | 0.000199 | m^2/min |
| | | | |
| | *S* | 0.011088 | m/min^1/2 |
| | | | |
| | *I* | 0.3206 | m^3/min |
| | | | |
| | | | |
| **Raghuwanshi** | *Xmax* | 1050.0 | m |
| | | | |
| | *Theta* | 0.0026669 | |
| | | | |
| | *f o* | 0.0004384 | m^3/min/m |
| | | | |
| | *F* | 0.255153 | |
| | | | |
| | *I* | 0.36977 | m^3/min |

| | | | |
|---|---|---|---|
| **Linear Infil** | *r* | 0.7203 | |
| | | | |
| | *fo* | 0.0003739 | m^3/min/m |
| | | | |
| | *Zcr* | 0.14554 | m^3 |

| Time (min) | Cumulative Infiltration $m^3/m$ | | | | | |
|---|---|---|---|---|---|---|
| | **Two Point** | **INFILT** | **Shepard** | **Raghu** | **Valiant** | **Linear** |
| 0 | 0.0000 | 0.0000 | 0.000000 | 0 | 0.00700 | 0.14554 |
| 5 | 0.0729 | 0.1137 | 0.025788 | 0.0055713 | 0.01542 | 0.14741 |
| 10 | 0.0908 | 0.1239 | 0.037053 | 0.0110979 | 0.02165 | 0.14928 |
| 20 | 0.1132 | 0.1362 | 0.053567 | 0.022019 | 0.03249 | 0.15302 |
| 40 | 0.1411 | 0.1522 | 0.078088 | 0.0433499 | 0.05136 | 0.16050 |
| 60 | 0.1605 | 0.1645 | 0.097829 | 0.0640282 | 0.06833 | 0.16798 |
| 80 | 0.1759 | 0.1751 | 0.115097 | 0.084088 | 0.08418 | 0.17545 |
| 100 | 0.1888 | 0.1848 | 0.130784 | 0.1035613 | 0.09924 | 0.18293 |
| 120 | 0.2000 | 0.1939 | 0.145347 | 0.1224786 | 0.11371 | 0.19041 |
| 140 | 0.2101 | 0.2026 | 0.159060 | 0.1408688 | 0.12770 | 0.19789 |
| 160 | 0.2192 | 0.2109 | 0.172099 | 0.1587592 | 0.14129 | 0.20537 |
| 180 | 0.2275 | 0.2191 | 0.184588 | 0.1761759 | 0.15454 | 0.21285 |
| 200 | 0.2353 | 0.2270 | 0.196616 | 0.1931433 | 0.16750 | 0.22033 |
| 240 | 0.2493 | 0.2424 | 0.219544 | 0.2258227 | 0.19267 | 0.23528 |
| 260 | 0.2557 | 0.2499 | 0.230539 | 0.2415778 | 0.20493 | 0.24276 |
| 280 | 0.2618 | 0.2573 | 0.241269 | 0.25697 | 0.21700 | 0.25024 |
| 300 | 0.2676 | 0.2646 | 0.251762 | 0.2720181 | 0.22891 | 0.25772 |
| 340 | 0.2785 | 0.2791 | 0.272127 | 0.3011528 | 0.25225 | 0.27268 |
| 380 | 0.2885 | 0.2933 | 0.291781 | 0.3291139 | 0.27504 | 0.28764 |
| 420 | 0.2978 | 0.3074 | 0.310834 | 0.3560202 | 0.29736 | 0.30259 |
| 460 | 0.3065 | 0.3212 | 0.329370 | 0.3819783 | 0.31925 | 0.31755 |

**Table A.10 Advance trajectories given by different methods for data set D5.**

| Time (min) | Advance Distance (m) | | | | | |
|---|---|---|---|---|---|---|
| | Two Point | INFILT | Shepard | Raghu | Valiant | Linear |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 26 | 17 | 47 | 28.94 | 54 | 13 |
| 10 | 45 | 32 | 79 | 56.33 | 97 | 26 |
| 20 | 77 | 61 | 130 | 106.92 | 164 | 51 |
| 40 | 130 | 112 | 205 | 194.09 | 261 | 100 |
| 60 | 176 | 159 | 264 | 266.50 | 329 | 147 |
| 80 | 217 | 203 | 313 | 327.61 | 383 | 192 |
| 100 | 256 | 245 | 355 | 379.88 | 427 | 234 |
| 120 | 292 | 284 | 393 | 425.10 | 464 | 275 |
| 140 | 327 | 322 | 427 | 464.60 | 496 | 314 |
| 160 | 361 | 358 | 458 | 499.41 | 524 | 351 |
| 180 | 393 | 392 | 487 | 530.30 | 550 | 387 |
| 200 | 424 | 426 | 514 | 557.92 | 573 | 422 |
| 240 | 484 | 488 | 564 | 605.19 | 613 | 487 |
| 260 | 513 | 518 | 586 | 625.57 | 630 | 517 |
| 280 | 541 | 547 | 608 | 644.17 | 647 | 547 |
| 300 | 569 | 575 | 628 | 661.21 | 662 | 575 |
| 340 | 622 | 628 | 666 | 691.32 | 691 | 629 |
| 380 | 674 | 678 | 701 | 717.11 | 716 | 680 |
| 420 | 724 | 725 | 734 | 739.44 | 739 | 727 |
| 460 | 773 | 769 | 764 | 758.96 | 760 | 771 |

**Table A.11 Advance data and cumulative infiltration given by different methods for data set D6.**

| | | | | | |
|---|---|---|---|---|---|
| **Constants** | | | | | |
| | | | | | |
| Cross sectional area | 0.038 | m^2 | | | |
| Discharge / inflow *Q* | 0.1175 | m^3/min | | | |
| Slope | Not given | % | | | |
| Furrow Length | 725 | m | | | |
| Run off | Not given | m^3/min | | | |
| Del y | 0.77 | | | | |
| | | | | | |
| **Data** | | | | | |
| | Distance | Advance Time | | | |
| | *x* | *t* | | | |
| | (m) | (min) | | | |
| | 0 | 0 | | | |
| | 150 | 52 | | | |
| | 300 | 123 | | | |
| | 450 | 210 | | | |
| | 600 | 317 | | | |
| | 725 | 416 | | | |
| **Valiantzas method** | | | Calculating alpha | Alpha | Alpha(new) |
| | *alpha* | 0.687 | | 0.8 | 0.800 |
| | | | | 0.79 | 0.790 |
| | *R* | 0.72229 | | 0.78 | 0.780 |
| | | | | 0.77 | 0.770 |
| | *Del z* | 0.65843 | | 0.76 | 0.760 |
| | | | | 0.687 | 0.687 |
| | *k* | 0.00075 | | | |
| | | | | | |
| | *F(alpha)* | -0.00016 | | | |
| | | | | | |
| | *dk / d(alpha)* | 0.00483 | | | |
| | | | | | |
| | *F'(alpha)* | 0.38711 | | | |
| | | | | | |
| | *alpha(new)* | 0.68742 | | | |
| | | | | | |
| | *I* | 0.05420 | m^3/m | | |

| | | |
|---|---|---|
| **INFILT** | *r* | 0.7293 |
| | *a* | 0.50698 |
| | *fo* | 0.00003 |
| | *k* | 0.002054 |
| | | |
| | *del z* | 0.716 |

| | | | |
|---|---|---|---|
| **Two Point** | *r* | 0.698 | |
| | | | |
| | *fo* | 0 | m^3/min/m |
| | | | |
| | *V L* | 0.0382 | m^2 |
| | | | |
| | *V 0.5L* | 0.0256 | m^2 |
| | | | |
| | *a* | 0.5855 | |
| | | | |
| | *del z* | 0.696 | |
| | | | |
| | *k* | 0.00160 | |

| | | | |
|---|---|---|---|
| **Shepard** | *A* | 0.000211 | m^2/min |
| | | | |
| | *S* | -0.001271 | m/min^1/2 |
| | | | |
| | *I* | 0.0619 | m^3/min |
| | | | |
| **Raghuwanshi** | | 1050.0 | m |
| | | | |
| | *Theta* | 0.0027713 | |
| | | | |
| | *f o* | 0.0001119 | m^3/min/m |
| | | | |
| | *F* | 0.023012 | |
| | | | |
| | *I* | 0.06230 | m^3/min |

| | | | |
|---|---|---|---|
| **Linear Infil** | *r* | 0.6977 | |
| | | | |
| | *fo* | 0.0001037 | m^3/min/m |
| | | | |
| | *Zcr* | 0.01274 | m^3 |

| Time (min) | Cumulative Infiltration m³/ m | | | | | |
|---|---|---|---|---|---|---|
| | Two Point | INFILT | Shepard | Raghu | Valiant | Linear |
| 0 | 0.0000 | 0.0000 | 0.000000 | 0 | 0.00700 | 0.01274 |
| 5 | 0.0041 | 0.0048 | 0.001687 | 0.0008762 | 0.00926 | 0.01326 |
| 10 | 0.0062 | 0.0069 | 0.001709 | 0.001748 | 0.01064 | 0.01378 |
| 20 | 0.0093 | 0.0100 | 0.001864 | 0.0034788 | 0.01286 | 0.01482 |
| 40 | 0.0139 | 0.0145 | 0.001902 | 0.0068906 | 0.01644 | 0.01689 |
| 60 | 0.0176 | 0.0182 | 0.002816 | 0.0102392 | 0.01947 | 0.01897 |
| 80 | 0.0209 | 0.0213 | 0.005513 | 0.0135279 | 0.02220 | 0.02104 |
| 100 | 0.0238 | 0.0242 | 0.008392 | 0.01676 | 0.02472 | 0.02312 |
| 120 | 0.0265 | 0.0269 | 0.011399 | 0.0199385 | 0.02708 | 0.02519 |
| 140 | 0.0290 | 0.0294 | 0.014503 | 0.0230662 | 0.02933 | 0.02726 |
| 160 | 0.0313 | 0.0317 | 0.017685 | 0.0261461 | 0.03147 | 0.02934 |
| 180 | 0.0335 | 0.0340 | 0.020930 | 0.0291805 | 0.03354 | 0.03141 |
| 200 | 0.0357 | 0.0361 | 0.024228 | 0.032172 | 0.03553 | 0.03349 |
| 240 | 0.0397 | 0.0403 | 0.030953 | 0.0380353 | 0.03934 | 0.03764 |
| 260 | 0.0416 | 0.0422 | 0.034369 | 0.0409114 | 0.04117 | 0.03971 |
| 280 | 0.0435 | 0.0441 | 0.037816 | 0.0437531 | 0.04295 | 0.04179 |
| 300 | 0.0452 | 0.0460 | 0.041289 | 0.0465623 | 0.04470 | 0.04386 |
| 340 | 0.0487 | 0.0496 | 0.048308 | 0.0520899 | 0.04809 | 0.04801 |
| 380 | 0.0520 | 0.0531 | 0.055408 | 0.0575072 | 0.05135 | 0.05216 |
| 420 | 0.0551 | 0.0565 | 0.062577 | 0.0628258 | 0.05451 | 0.05631 |
| 460 | 0.0581 | 0.0598 | 0.069806 | 0.0680559 | 0.05758 | 0.06046 |

**Table A.12 advance trajectories given by different methods for data set D6.**

| Time (min) | Advance Distance (m) | | | | | |
|---|---|---|---|---|---|---|
| | Two Point | INFILT | Shepard | Raghu | Valiant | Linear |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 18 | 18 | 21 | 27.42 | 16 | 14 |
| 10 | 35 | 34 | 43 | 53.44 | 30 | 28 |
| 20 | 66 | 65 | 85 | 101.70 | 59 | 54 |
| 40 | 121 | 119 | 164 | 185.44 | 111 | 106 |
| 60 | 170 | 168 | 235 | 255.60 | 159 | 154 |
| 80 | 215 | 213 | 298 | 315.22 | 203 | 200 |
| 100 | 256 | 254 | 352 | 366.51 | 245 | 244 |
| 120 | 296 | 294 | 400 | 411.12 | 285 | 286 |
| 140 | 333 | 331 | 443 | 450.25 | 323 | 325 |
| 160 | 368 | 366 | 480 | 484.87 | 359 | 363 |
| 180 | 402 | 400 | 513 | 515.71 | 394 | 399 |
| 200 | 434 | 433 | 543 | 543.36 | 427 | 433 |
| 240 | 495 | 494 | 593 | 590.88 | 490 | 498 |
| 260 | 525 | 523 | 614 | 611.45 | 520 | 528 |
| 280 | 553 | 551 | 633 | 630.25 | 549 | 557 |
| 300 | 580 | 578 | 651 | 647.50 | 577 | 584 |
| 340 | 632 | 630 | 681 | 678.08 | 631 | 636 |
| 380 | 682 | 679 | 706 | 704.35 | 682 | 685 |
| 420 | 730 | 726 | 727 | 727.14 | 731 | 729 |
| 460 | 775 | 770 | 745 | 747.12 | 777 | 771 |

**Table A.13 Advance data and cumulative infiltration given by different methods for data set D7**.

| | | | | |
|---|---|---|---|---|
| **Constants** | | | | |
| Cross sectional area | 0.038 | M^2 | | |
| Discharge / inflow *Q* | 0.2412 | M^3/min | | |
| Slope | 0.1 | % | | |
| Furrow Length | 882 | M | | |
| Run off | Not given | M^3/min | | |
| Del y | 0.77 | | | |
| **Data** | | | | |
| | Distance | Advance time | | |
| | *x* | *t* | | |
| | (m) | (min) | | |
| | 0 | 0 | | |
| | 230 | 218 | | |
| | 470 | 551 | | |
| | 882 | 1349 | | |
| **Valiantzas method** | | | Alpha | Alpha(new) |
| | *alpha* | 0.776 | 0.8 | 0.800 |
| | | | 0.79 | 0.790 |
| | *R* | 0.32164 | 0.78 | 0.780 |
| | | | 0.77 | 0.770 |
| | *Del z* | 0.78733 | 0.76 | 0.760 |
| | | | 0.776 | 0.776 |
| | *k* | 0.00158 | | |
| | | | | |
| | *F(alpha)* | 0.00204 | | |
| | | | | |
| | *dk / d(alpha)* | 0.02102 | | |
| | | | | |
| | *F'(alpha)* | 6.85516 | | |
| | | | | |
| | *alpha(new)* | 0.77570 | | |
| | | | | |
| | *I* | 0.43118 | m^3/m | |

| | | |
|---|---|---|
| **INFILT** | *r* | 0.7742 |
| | *a* | 0.20912 |
| | *fo* | 0.000083 |
| | *k* | 0.070911 |
| | | |
| | *del z* | 0.849 |

| | | | |
|---|---|---|---|
| **Two Point** | *r* | 0.703 | |
| | | | |
| | *fo* | 0 | m^3/min/m |
| | | | |
| | *V L* | 0.3397 | m^2 |
| | | | |
| | *V 0.5L* | 0.2535 | m^2 |
| | | | |
| | *a* | 0.3267 | |
| | | | |
| | *del z* | 0.797 | |
| | | | |
| | *k* | 0.04047 | |

| | | | |
|---|---|---|---|
| **Shepard** | *A* | 0.000065 | m^2/min |
| | | | |
| | *S* | 0.009746 | m/min^1/2 |
| | | | |
| | *I* | 0.4457 | m^3/min |
| | | | |
| | | | |
| **Raghuwanshi** | *x max* | 1150.0 | m |
| | | | |
| | | | |
| | *Theta* | 0.0010190 | |
| | | | |
| | | | |
| | | | |
| | *f o* | 0.0002097 | m^3/min/m |
| | | | |
| | *F* | 0.303225 | |
| | | | |
| | *I* | 0.50946 | m^3/min |

| | | | |
|---|---|---|---|
| **Linear Infil** | *r* | 0.7030 | |
| | | | |
| | *fo* | 0.0001838 | m^3/min/m |
| | | | |
| | *Zcr* | 0.19403 | m^3 |

| Time (min) | Cumulative Infiltration $m^3/m$ | | | | | |
|---|---|---|---|---|---|---|
| | Two Point | INFILT | Shepard | Raghu | Valiant | Linear |
| 0 | 0.0000 | 0.0000 | 0.000000 | 0 | 0.00700 | 0.19403 |
| 5 | 0.0685 | 0.0997 | 0.022117 | 0.0025895 | 0.01252 | 0.19495 |
| 10 | 0.0859 | 0.1156 | 0.031469 | 0.0051711 | 0.01645 | 0.19587 |
| 20 | 0.1077 | 0.1343 | 0.044885 | 0.0103111 | 0.02317 | 0.19771 |
| 40 | 0.1351 | 0.1567 | 0.064240 | 0.0204988 | 0.03469 | 0.20138 |
| 60 | 0.1542 | 0.1719 | 0.079394 | 0.0305657 | 0.04492 | 0.20506 |
| 80 | 0.1694 | 0.1839 | 0.092374 | 0.0405141 | 0.05440 | 0.20874 |
| 100 | 0.1822 | 0.1941 | 0.103964 | 0.0503465 | 0.06336 | 0.21241 |
| 120 | 0.1934 | 0.2029 | 0.114567 | 0.0600651 | 0.07193 | 0.21609 |
| 140 | 0.2034 | 0.2109 | 0.124422 | 0.0696723 | 0.08017 | 0.21977 |
| 160 | 0.2124 | 0.2182 | 0.133685 | 0.0791703 | 0.08816 | 0.22344 |
| 180 | 0.2208 | 0.2250 | 0.142465 | 0.0885614 | 0.09592 | 0.22712 |
| 200 | 0.2285 | 0.2313 | 0.150839 | 0.0978477 | 0.10350 | 0.23080 |
| 240 | 0.2425 | 0.2430 | 0.166596 | 0.1161142 | 0.11815 | 0.23815 |
| 260 | 0.2490 | 0.2484 | 0.174062 | 0.1250985 | 0.12527 | 0.24183 |
| 280 | 0.2551 | 0.2536 | 0.181296 | 0.1339862 | 0.13227 | 0.24550 |
| 300 | 0.2609 | 0.2586 | 0.188321 | 0.1427793 | 0.13916 | 0.24918 |
| 340 | 0.2718 | 0.2682 | 0.201825 | 0.160089 | 0.15264 | 0.25653 |
| 380 | 0.2818 | 0.2771 | 0.214705 | 0.1770425 | 0.16576 | 0.26389 |
| 420 | 0.2912 | 0.2856 | 0.227056 | 0.193654 | 0.17857 | 0.27124 |
| 460 | 0.3000 | 0.2938 | 0.238954 | 0.2099372 | 0.19112 | 0.27859 |
| 500 | 0.3083 | 0.3016 | 0.250455 | 0.2259051 | 0.20342 | 0.28595 |
| 540 | 0.3161 | 0.3091 | 0.261607 | 0.2415704 | 0.21550 | 0.29330 |
| 580 | 0.3236 | 0.3164 | 0.272448 | 0.2569451 | 0.22739 | 0.30065 |
| 620 | 0.3307 | 0.3235 | 0.283009 | 0.2720409 | 0.23909 | 0.30801 |
| 680 | 0.3408 | 0.3338 | 0.298384 | 0.2941858 | 0.25633 | 0.31904 |
| 735 | 0.3496 | 0.3429 | 0.312040 | 0.3139864 | 0.27184 | 0.32915 |
| 800 | 0.3594 | 0.3534 | 0.327705 | 0.3368083 | 0.28983 | 0.34110 |
| 900 | 0.3735 | 0.3688 | 0.350933 | 0.3707826 | 0.31689 | 0.35948 |
| 1000 | 0.3866 | 0.3837 | 0.373256 | 0.4034975 | 0.34328 | 0.37786 |
| 1100 | 0.3988 | 0.3980 | 0.394805 | 0.4350751 | 0.36908 | 0.39625 |
| 1200 | 0.4103 | 0.4119 | 0.415684 | 0.4656256 | 0.39436 | 0.41463 |
| 1300 | 0.4212 | 0.4255 | 0.435977 | 0.4952484 | 0.41918 | 0.43301 |
| 1349 | 0.4263 | 0.4320 | 0.445726 | 0.5094525 | 0.43118 | 0.44202 |

**Table A.14 Advance trajectories given by different methods for data set D7.**

| Time (min) | Advance Distance (m) | | | | | |
|---|---|---|---|---|---|---|
| | Two Point | INFILT | Shepard | Raghu | Valiant | Linear |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 14 | 11 | 26 | 13.86 | 30 | 5 |
| 10 | 25 | 19 | 45 | 27.39 | 55 | 11 |
| 20 | 42 | 34 | 75 | 53.50 | 98 | 21 |
| 40 | 70 | 60 | 122 | 102.24 | 166 | 42 |
| 60 | 95 | 83 | 159 | 146.84 | 219 | 63 |
| 80 | 118 | 105 | 191 | 187.79 | 262 | 83 |
| 100 | 138 | 126 | 219 | 225.53 | 299 | 103 |
| 120 | 158 | 146 | 245 | 260.43 | 331 | 123 |
| 140 | 177 | 165 | 268 | 292.78 | 360 | 142 |
| 160 | 194 | 183 | 290 | 322.86 | 385 | 160 |
| 180 | 212 | 201 | 311 | 350.91 | 409 | 179 |
| 200 | 228 | 218 | 330 | 377.11 | 430 | 197 |
| 240 | 260 | 252 | 366 | 424.68 | 468 | 232 |
| 260 | 276 | 268 | 382 | 446.34 | 485 | 249 |
| 280 | 291 | 284 | 398 | 466.73 | 501 | 266 |
| 300 | 305 | 299 | 414 | 485.98 | 516 | 283 |
| 340 | 334 | 330 | 443 | 521.40 | 543 | 315 |
| 380 | 361 | 359 | 470 | 553.23 | 568 | 347 |
| 420 | 388 | 387 | 496 | 582.00 | 591 | 377 |
| 460 | 414 | 414 | 520 | 608.12 | 612 | 406 |
| 500 | 439 | 441 | 543 | 631.94 | 632 | 435 |
| 540 | 463 | 467 | 565 | 653.75 | 650 | 463 |
| 580 | 487 | 492 | 586 | 673.81 | 667 | 489 |
| 620 | 511 | 517 | 606 | 692.30 | 683 | 515 |
| 680 | 545 | 553 | 635 | 717.50 | 705 | 553 |
| 735 | 576 | 585 | 660 | 738.27 | 724 | 586 |
| 800 | 611 | 622 | 688 | 760.39 | 745 | 623 |
| 900 | 664 | 676 | 729 | 790.14 | 775 | 677 |
| 1000 | 715 | 728 | 766 | 815.66 | 801 | 728 |
| 1100 | 765 | 778 | 802 | 837.80 | 826 | 776 |
| 1200 | 813 | 826 | 835 | 857.20 | 848 | 820 |
| 1300 | 859 | 872 | 867 | 874.32 | 869 | 862 |
| 1349 | 882 | 894 | 882 | 882.00 | 879 | 882 |

**Table A.15 Advance data and cumulative infiltration given by different methods for data set D8.**

| | | | | | |
|---|---|---|---|---|---|
| **Constants** | | | | | |
| | | | | | |
| Cross sectional area | 0.038 | m^2 | | | |
| Discharge / inflow *Q* | 0.276 | m^3/min | | | |
| Slope | Not given | % | | | |
| Furrow Length | 625 | m | | | |
| Run off | Not given | m^3/min | | | |
| Del y | 0.77 | | | | |
| | | | | | |
| **Data** | | | | | |
| | Distance | Advance time | | | |
| | *x* | *t* | | | |
| | (m) | (min) | | | |
| | 0 | 0 | | | |
| | 250 | 133 | | | |
| | 375 | 244 | | | |
| | 500 | 327 | | | |
| | 625 | 440 | | | |
| **Valiantzas method** | | | | Alpha | Alpha(new) |
| | *alpha* | 0.784 | | 0.8 | 0.800 |
| | | | | 0.79 | 0.790 |
| | *R* | 0.39833 | | 0.78 | 0.780 |
| | | | | 0.77 | 0.770 |
| | *Del z* | 0.74963 | | 0.76 | 0.760 |
| | | | | 0.784 | 0.784 |
| | *k* | 0.00178 | | | |
| | | | | | |
| | *F(alpha)* | -0.00077 | | | |
| | | | | | |
| | *dk / d(alpha)* | 0.02742 | | | |
| | | | | | |
| | *F' (alpha)* | 3.38632 | | | |
| | | | | | |
| | *alpha(new)* | 0.78423 | | | |

| | | |
|---|---|---|
| **INFILT** | *r* | 0.7742 |
| | *a* | 0.24509 |
| | *fo* | 0 |
| | *k* | 0.04508 |
| | | |
| | *del z* | 0.828 |

| | | | |
|---|---|---|---|
| **Two Point** | *r* | 0.866 | |
| | | | |
| | *fo* | 0 | m^3/min/m |
| | | | |
| | *V L* | 0.1650 | m^2 |
| | | | |
| | *V 0.5L* | 0.1503 | m^2 |
| | | | |
| | *a* | 0.1584 | |
| | | | |
| | *del z* | 0.873 | |
| | | | |
| | *k* | 0.07207 | |

| | | | |
|---|---|---|---|
| **Shepard** | *A* | 0.000200 | m^2/min |
| | | | |
| | *S* | 0.006466 | m/min^1/2 |
| | | | |
| | *I* | 0.2234 | m^3/min |
| | | | |
| | | | |
| **Raghuwanshi** | *x max* | 1150.0 | m |
| | | | |
| | *Theta* | 0.0017468 | |
| | | | |
| | *f o* | 0.0002400 | m^3/min/m |
| | | | |
| | *F* | 0.305137 | |
| | | | |
| | *I* | 0.26926 | m^3/min |

| | | | |
|---|---|---|---|
| **Linear Infil** | *r* | 0.8664 | |
| | | | |
| | *fo* | 0.0001402 | m^3/min/m |
| | | | |
| | *Zcr* | 0.13200 | m^3 |

| Time (min) | Cumulative Infiltration $m^3/m$ | | | | | |
|---|---|---|---|---|---|---|
| | Two Point | INFILT | Shepard | Raghu | Valiant | Linear |
| 0 | 0.0000 | 0.0000 | 0.000000 | 0 | 0.00700 | 0.13200 |
| 5 | 0.0930 | 0.0669 | 0.015456 | 0.0038532 | 0.01327 | 0.13270 |
| 10 | 0.1038 | 0.0793 | 0.022442 | 0.0076834 | 0.01780 | 0.13340 |
| 20 | 0.1158 | 0.0939 | 0.032907 | 0.0152753 | 0.02561 | 0.13480 |
| 40 | 0.1293 | 0.1113 | 0.048874 | 0.030191 | 0.03904 | 0.13761 |
| 60 | 0.1379 | 0.1230 | 0.062055 | 0.0447595 | 0.05104 | 0.14041 |
| 80 | 0.1443 | 0.1320 | 0.073793 | 0.0589926 | 0.06218 | 0.14321 |
| 100 | 0.1495 | 0.1394 | 0.084609 | 0.0729018 | 0.07273 | 0.14602 |
| 120 | 0.1539 | 0.1457 | 0.094771 | 0.0864984 | 0.08284 | 0.14882 |
| 140 | 0.1577 | 0.1513 | 0.104436 | 0.0997929 | 0.09258 | 0.15162 |
| 160 | 0.1611 | 0.1564 | 0.113708 | 0.1127958 | 0.10203 | 0.15443 |
| 180 | 0.1641 | 0.1610 | 0.122660 | 0.1255172 | 0.11123 | 0.15723 |
| 200 | 0.1668 | 0.1652 | 0.131342 | 0.1379666 | 0.12021 | 0.16003 |
| 240 | 0.1717 | 0.1727 | 0.148050 | 0.1620865 | 0.13761 | 0.16564 |
| 260 | 0.1739 | 0.1761 | 0.156130 | 0.1737749 | 0.14607 | 0.16844 |
| 280 | 0.1760 | 0.1794 | 0.164056 | 0.1852267 | 0.15439 | 0.17125 |
| 300 | 0.1779 | 0.1824 | 0.171843 | 0.1964502 | 0.16258 | 0.17405 |
| 340 | 0.1815 | 0.1881 | 0.187056 | 0.2182432 | 0.17863 | 0.17966 |
| 380 | 0.1847 | 0.1933 | 0.201854 | 0.2392133 | 0.19427 | 0.18526 |
| 420 | 0.1877 | 0.1981 | 0.216302 | 0.2594162 | 0.20956 | 0.19087 |
| 440 | 0.1890 | 0.2004 | 0.223411 | 0.2692463 | 0.21709 | 0.19367 |

**Table A.16 Advance trajectories given by different methods for data set D8.**

| Time (min) | Advance Distance (m) | | | | | |
|---|---|---|---|---|---|---|
| | Two Point | INFILT | Shepard | Raghu | Valiant | Linear |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 12 | 16 | 33 | 15.35 | 34 | 9 |
| 10 | 23 | 29 | 59 | 30.30 | 62 | 17 |
| 20 | 42 | 52 | 101 | 59.03 | 110 | 34 |
| 40 | 78 | 91 | 166 | 112.30 | 183 | 67 |
| 60 | 111 | 126 | 216 | 160.61 | 239 | 100 |
| 80 | 142 | 159 | 259 | 204.63 | 284 | 132 |
| 100 | 173 | 191 | 296 | 244.89 | 323 | 164 |
| 120 | 202 | 221 | 328 | 281.86 | 356 | 195 |
| 140 | 231 | 250 | 358 | 315.93 | 385 | 225 |
| 160 | 260 | 278 | 385 | 347.43 | 411 | 255 |
| 180 | 288 | 306 | 409 | 376.64 | 434 | 284 |
| 200 | 316 | 332 | 432 | 403.79 | 456 | 313 |
| 240 | 370 | 384 | 474 | 452.76 | 494 | 369 |
| 260 | 396 | 410 | 492 | 474.90 | 511 | 397 |
| 280 | 423 | 435 | 510 | 495.69 | 527 | 424 |
| 300 | 449 | 459 | 527 | 515.23 | 542 | 451 |
| 340 | 500 | 507 | 558 | 551.01 | 569 | 502 |
| 380 | 551 | 554 | 587 | 582.98 | 594 | 553 |
| 420 | 600 | 600 | 613 | 611.70 | 616 | 601 |
| 440 | 625 | 622 | 625 | 625.00 | 627 | 625 |

**Table A.17 Advance data and cumulative infiltration given by different methods for data set D9.**

| | | | | | |
|---|---|---|---|---|---|
| **Constants** | | | | | |
| | | | | | |
| Cross sectional area | 0.038 | m^2 | | | |
| Discharge / inflow *Q* | 0.1758 | m^3/min | | | |
| Slope | Not given | % | | | |
| Furrow Length | 608 | m | | | |
| Run off | Not given | m^3/min | | | |
| Del y | 0.77 | | | | |
| | | | | | |
| **Data** | | | | | |
| | Distance | Advance time | | | |
| | *x* | *t* | | | |
| | (m) | (min) | | | |
| | 0 | 0 | | | |
| | 125 | 48 | | | |
| | 375 | 158 | | | |
| | 500 | 230 | | | |
| | 608 | 289 | | | |
| **Valiantzas method** | | | | Alpha | Alpha(new) |
| | *alpha* | 0.738 | | 0.8 | 0.800 |
| | | | | 0.79 | 0.790 |
| | *R* | 0.62915 | | 0.78 | 0.780 |
| | | | | 0.77 | 0.770 |
| | *Del z* | 0.67203 | | 0.76 | 0.760 |
| | | | | 0.738 | 0.738 |
| | *k* | 0.00108 | | | |
| | | | | | |
| | *F(alpha)* | 0.00003 | | | |
| | | | | | |
| | *dk / d(alpha)* | 0.00880 | | | |
| | | | | | |
| | *F'(alpha)* | 0.65533 | | | |
| | | | | | |
| | *alpha(new)* | 0.73796 | | | |
| | | | | | |
| | *I* | 0.07741 | m^3/m | | |

| | | |
|---|---|---|
| **INFILT** | *r* | 0.7742 |
| | *a* | 0.014 |
| | *fo* | 0.000123 |
| | *k* | 0.033125 |
| | | |
| | *del z* | 0.988 |

| | | | |
|---|---|---|---|
| **Two Point** | *r* | 0.800 | |
| | | | |
| | *fo* | 0 | m^3/min/m |
| | | | |
| | *V L* | 0.0543 | m^2 |
| | | | |
| | *V 0.5L* | 0.0448 | m^2 |
| | | | |
| | *a* | 0.3182 | |
| | | | |
| | *del z* | 0.785 | |
| | | | |
| | *k* | 0.01139 | |

| | | | |
|---|---|---|---|
| **Shepard** | *A* | 0.000304 | m^2/min |
| | | | |
| | *S* | -0.000316 | m/min^1/2 |
| | | | |
| | *I* | 0.0824 | m^3/min |
| | | | |
| | | | |
| **Raghuwanshi** | *x max* | 1050.0 | m |
| | | | |
| | *Theta* | 0.0028106 | |
| | | | |
| | *f o* | 0.0001674 | m^3/min/m |
| | | | |
| | *F* | 0.074017 | |
| | | | |
| | *I* | 0.08955 | m^3/min |

| | | | |
|---|---|---|---|
| **Linear Infil** | *r* | 0.8003 | |
| | | | |
| | *fo* | 0.0001305 | m^3/min/m |
| | | | |
| | *Zcr* | 0.03336 | m^3 |

| Time (min) | Cumulative Infiltration m³/ m | | | | | |
|---|---|---|---|---|---|---|
| | Two Point | INFILT | Shepard | Raghu | Valiant | Linear |
| 0 | 0.0000 | 0.0000 | 0.000000 | 0 | 0.00700 | 0.03336 |
| 5 | 0.0190 | 0.0345 | 0.000812 | 0.0018699 | 0.01053 | 0.03401 |
| 10 | 0.0237 | 0.0354 | 0.002039 | 0.0037254 | 0.01288 | 0.03467 |
| 20 | 0.0296 | 0.0370 | 0.004662 | 0.007394 | 0.01681 | 0.03597 |
| 40 | 0.0369 | 0.0398 | 0.010152 | 0.0145669 | 0.02336 | 0.03858 |
| 60 | 0.0419 | 0.0425 | 0.015778 | 0.0215308 | 0.02907 | 0.04119 |
| 80 | 0.0459 | 0.0451 | 0.021474 | 0.0282971 | 0.03429 | 0.04380 |
| 100 | 0.0493 | 0.0476 | 0.027215 | 0.0348766 | 0.03918 | 0.04641 |
| 120 | 0.0523 | 0.0502 | 0.032988 | 0.0412796 | 0.04381 | 0.04902 |
| 140 | 0.0549 | 0.0527 | 0.038786 | 0.0475155 | 0.04824 | 0.05162 |
| 160 | 0.0573 | 0.0552 | 0.044603 | 0.0535937 | 0.05252 | 0.05423 |
| 180 | 0.0595 | 0.0578 | 0.050435 | 0.0595227 | 0.05665 | 0.05684 |
| 200 | 0.0615 | 0.0603 | 0.056281 | 0.0653106 | 0.06066 | 0.05945 |
| 240 | 0.0652 | 0.0653 | 0.068004 | 0.0764938 | 0.06839 | 0.06467 |
| 260 | 0.0669 | 0.0678 | 0.073879 | 0.0819032 | 0.07213 | 0.06728 |
| 280 | 0.0684 | 0.0703 | 0.079761 | 0.0872 | 0.07579 | 0.06989 |
| 289 | 0.0691 | 0.0714 | 0.082411 | 0.0895485 | 0.07741 | 0.07106 |

**Table A.18 Advance trajectories given by different methods for data set D9.**

| Time (min) | Advance Distance (m) | | | | | |
|---|---|---|---|---|---|---|
| | Two Point | INFILT | Shepard | Raghu | Valiant | Linear |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 20 | 14 | 30 | 24.41 | 23 | 14 |
| 10 | 37 | 28 | 58 | 47.71 | 44 | 28 |
| 20 | 67 | 54 | 109 | 91.27 | 82 | 55 |
| 40 | 121 | 106 | 196 | 167.94 | 149 | 107 |
| 60 | 170 | 155 | 267 | 233.25 | 206 | 158 |
| 80 | 215 | 202 | 325 | 289.56 | 258 | 206 |
| 100 | 259 | 247 | 374 | 338.61 | 304 | 252 |
| 120 | 300 | 291 | 415 | 381.71 | 346 | 296 |
| 140 | 340 | 332 | 450 | 419.89 | 385 | 338 |
| 160 | 379 | 373 | 481 | 453.94 | 421 | 379 |
| 180 | 417 | 411 | 507 | 484.50 | 454 | 418 |
| 200 | 453 | 449 | 531 | 512.08 | 486 | 456 |
| 240 | 524 | 519 | 570 | 559.88 | 544 | 527 |
| 260 | 559 | 553 | 587 | 580.73 | 571 | 561 |
| 280 | 593 | 585 | 602 | 599.88 | 597 | 594 |
| 289 | 608 | 600 | 608 | 608.00 | 608 | 608 |

**Table A.19 Advance data and cumulative infiltration given by different methods for data set D10**

| | | | | | |
|---|---|---|---|---|---|
| **Constants** | | | | | |
| | | | | | |
| Cross sectional area | | 0.038 | m^2 | | |
| Discharge / inflow *Q* | *Q* | 0.3972 | m^3/min | | |
| Slope | | Not given | % | | |
| Furrow Length | | 700 | m | | |
| Run off | | Not given | m^3/min | | |
| Del y | | 0.77 | | | |
| | | | | | |
| **Data** | | | | | |
| | Distance | Advance Time | | | |
| | *x* | *t* | | | |
| | (m) | (min) | | | |
| | 0 | 0 | | | |
| | 140 | 90 | | | |
| | 420 | 314 | | | |
| | 560 | 439 | | | |
| | 700 | 558 | | | |
| **Valiantzas method** | | | | Alpha | Alpha(new) |
| | *alpha* | 0.798 | | 0.8 | 0.800 |
| | | | | 0.79 | 0.790 |
| | *R* | 0.31916 | | 0.78 | 0.780 |
| | | | | 0.77 | 0.770 |
| | *Del z* | 0.78524 | | 0.76 | 0.760 |
| | | | | 0.798 | 0.798 |
| | *k* | 0.00228 | | | |
| | | | | | |
| | *F(alpha)* | -0.00195 | | | |
| | | | | | |
| | *dk / d(alpha)* | 0.04680 | | | |
| | | | | | |
| | *F'(alpha)* | 7.47654 | | | |
| | | | | | |
| | *alpha(new)* | 0.79826 | | | |
| | | | | | |
| | *I* | 0.36214 | m^3/m | | |

| | | |
|---|---|---|
| **INFILT** | *r* | 0.7742 |
| | *a* | 0.1272 |
| | *fo* | 0 |
| | *k* | 0.14418 |
| | | |
| | *del z* | 0.902 |

| | | | |
|---|---|---|---|
| **Two Point** | *r* | 0.888 | |
| | | | |
| | *fo* | 0 | m^3/min/m |
| | | | |
| | *V L* | 0.2874 | m^2 |
| | | | |
| | *V 0.5L* | 0.2677 | m^2 |
| | | | |
| | *a* | 0.1233 | |
| | | | |
| | *del z* | 0.897 | |
| | | | |
| | *k* | 0.14691 | |

| | | | |
|---|---|---|---|
| **Shepard** | *A* | 0.000157 | m^2/min |
| | | | |
| | *S* | 0.012335 | m/min^1/2 |
| | | | |
| | *I* | 0.3792 | m^3/min |
| | | | |
| | | | |
| **Raghuwanshi** | *Xmax* | 1150.0 | m |
| | | | |
| | *Theta* | 0.0015229 | |
| | | | |
| | *f o* | 0.0003454 | m^3/min/m |
| | | | |
| | *F* | 0.435380 | |
| | | | |
| | *I* | 0.44198 | m^3/min |

| | | | |
|---|---|---|---|
| **Linear Infil** | *r* | 0.8884 | |
| | | | |
| | *fo* | 0.0001522 | m^3/min/m |
| | | | |
| | *Zcr* | 0.24238 | m^3 |

| Time (min) | Cumulative Infiltration m³/ m | | | | | |
|---|---|---|---|---|---|---|
| | Two Point | INFILT | Shepard | Raghu | Valiant | Linear |
| 0 | 0.0000 | 0.0000 | 0.000000 | 0 | 0.00700 | 0.24238 |
| 5 | 0.1792 | 0.1769 | 0.028368 | 0.0050292 | 0.01524 | 0.24314 |
| 10 | 0.1952 | 0.1932 | 0.040579 | 0.0100333 | 0.02133 | 0.24390 |
| 20 | 0.2126 | 0.2111 | 0.058309 | 0.0199671 | 0.03191 | 0.24543 |
| 40 | 0.2315 | 0.2305 | 0.084305 | 0.0395425 | 0.05032 | 0.24847 |
| 60 | 0.2434 | 0.2427 | 0.104984 | 0.0587379 | 0.06688 | 0.25151 |
| 80 | 0.2522 | 0.2518 | 0.122911 | 0.0775648 | 0.08234 | 0.25456 |
| 100 | 0.2592 | 0.2590 | 0.139080 | 0.0960341 | 0.09703 | 0.25760 |
| 120 | 0.2651 | 0.2651 | 0.153999 | 0.1141567 | 0.11114 | 0.26065 |
| 140 | 0.2702 | 0.2703 | 0.167972 | 0.1319429 | 0.12477 | 0.26369 |
| 160 | 0.2747 | 0.2750 | 0.181195 | 0.1494027 | 0.13802 | 0.26674 |
| 180 | 0.2787 | 0.2791 | 0.193806 | 0.1665461 | 0.15093 | 0.26978 |
| 200 | 0.2824 | 0.2829 | 0.205904 | 0.1833824 | 0.16356 | 0.27283 |
| 240 | 0.2888 | 0.2895 | 0.228846 | 0.2161707 | 0.18809 | 0.27892 |
| 260 | 0.2917 | 0.2925 | 0.239795 | 0.2321401 | 0.20004 | 0.28196 |
| 280 | 0.2943 | 0.2952 | 0.250449 | 0.2478378 | 0.21180 | 0.28501 |
| 300 | 0.2969 | 0.2978 | 0.260840 | 0.2632718 | 0.22340 | 0.28805 |
| 340 | 0.3015 | 0.3026 | 0.280930 | 0.2933802 | 0.24614 | 0.29414 |
| 380 | 0.3056 | 0.3069 | 0.300229 | 0.3225259 | 0.26834 | 0.30023 |
| 420 | 0.3094 | 0.3109 | 0.318861 | 0.3507657 | 0.29008 | 0.30632 |
| 460 | 0.3129 | 0.3145 | 0.336917 | 0.3781532 | 0.31140 | 0.31241 |
| 500 | 0.3162 | 0.3178 | 0.354472 | 0.4047388 | 0.33235 | 0.31850 |
| 540 | 0.3192 | 0.3210 | 0.371585 | 0.4305697 | 0.35297 | 0.32459 |
| 588 | 0.3225 | 0.3245 | 0.391604 | 0.4606334 | 0.37730 | 0.33190 |

**Table A.20 Advance trajectories given by different methods for data set D10.**

| Time (min)e | Advance Distance (m) | | | | | |
|---|---|---|---|---|---|---|
| | Two Point | INFILT | Shepard | Raghu | Valiant | Linear |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 10 | 11 | 39 | 15.81 | 46 | 7 |
| 10 | 19 | 20 | 65 | 31.19 | 84 | 15 |
| 20 | 36 | 36 | 106 | 60.73 | 142 | 29 |
| 40 | 67 | 67 | 168 | 115.37 | 226 | 58 |
| 60 | 96 | 96 | 215 | 164.79 | 286 | 86 |
| 80 | 124 | 124 | 256 | 209.70 | 333 | 114 |
| 100 | 152 | 151 | 291 | 250.70 | 371 | 142 |
| 120 | 179 | 178 | 322 | 288.27 | 404 | 169 |
| 140 | 205 | 204 | 351 | 322.83 | 432 | 197 |
| 160 | 231 | 229 | 377 | 354.72 | 457 | 223 |
| 180 | 256 | 255 | 401 | 384.25 | 479 | 250 |
| 200 | 281 | 279 | 424 | 411.66 | 499 | 276 |
| 240 | 331 | 328 | 466 | 460.99 | 534 | 328 |
| 260 | 355 | 353 | 485 | 483.26 | 550 | 353 |
| 280 | 379 | 376 | 504 | 504.14 | 564 | 378 |
| 300 | 403 | 400 | 521 | 523.75 | 578 | 403 |
| 340 | 451 | 447 | 554 | 559.60 | 603 | 452 |
| 380 | 498 | 493 | 585 | 591.57 | 625 | 499 |
| 420 | 544 | 539 | 614 | 620.25 | 645 | 546 |
| 460 | 590 | 584 | 640 | 646.14 | 664 | 592 |
| 500 | 635 | 629 | 666 | 669.61 | 681 | 637 |
| 540 | 680 | 673 | 690 | 690.99 | 697 | 681 |
| 588 | 733 | 726 | 717 | 714.26 | 714 | 732 |

# APPENDIX B: Actual INFILT Values, Scaling Factors, Actual and Scaled Cumulative Infiltration Depths for the Fields T and C

### Table B.1 INFILT infiltration parameters and actual cumulative infiltration for field T

| | INFILT Values | T1 | T 2 | T 3 | T 4 | T5 |
|---|---|---|---|---|---|---|
| | | | | | | |
| | *a* | 0.07208 | 0.05673 | 0.05106 | 0.11268 | 0.09838 |
| | *k* m^3/min^a/m | 0.09859 | 0.11336 | 0.13082 | 0.07201 | 0.09995 |
| | $f_o$ m^3/min/m | 0 | 0 | 0 | 0 | 0 |
| | | | | | | |
| ***t* (min)** | | ***I* m³/m** | | | | |
| 0 | | 0 | 0 | 0 | 0 | 0 |
| 20 | | 0.12235201 | 0.134359 | 0.152442 | 0.100924 | 0.134208 |
| 50 | | 0.130705729 | 0.141528 | 0.159744 | 0.111901 | 0.146868 |
| 100 | | 0.137401941 | 0.147204 | 0.165499 | 0.120991 | 0.157233 |
| 200 | | 0.144441207 | 0.153108 | 0.171461 | 0.13082 | 0.168329 |
| 300 | | 0.148724928 | 0.15667 | 0.175048 | 0.136935 | 0.175179 |
| 400 | | 0.151841103 | 0.159248 | 0.177638 | 0.141447 | 0.180208 |
| 500 | | 0.15430309 | 0.161277 | 0.179673 | 0.145048 | 0.184208 |
| 600 | | 0.156344284 | 0.162954 | 0.181354 | 0.148059 | 0.187541 |
| 700 | | 0.158091141 | 0.164385 | 0.182787 | 0.150653 | 0.190407 |
| 800 | | 0.159620105 | 0.165635 | 0.184037 | 0.152937 | 0.192925 |
| 900 | | 0.160981017 | 0.166745 | 0.185147 | 0.15498 | 0.195174 |
| 1000 | | 0.162208223 | 0.167745 | 0.186146 | 0.156831 | 0.197207 |

| T 6 | T 7 | T 8 | T 9 | T 10 | T 11 | T 12 | T 13 |
|---|---|---|---|---|---|---|---|
| 0.23808 | 0.17475 | 0.09127 | 0.16712 | 0.16712 | 0.15013 | 0.11144 | 0.16771 |
| 0.04291 | 0.06872 | 0.11044 | 0.07384 | 0.07384 | 0.08167 | 0.0657 | 0.04395 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| ***I* m³/m** | | | | | | | |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.08756 | 0.115995 | 0.145168 | 0.12182 | 0.12182 | 0.128052 | 0.091739 | 0.072636 |
| 0.108905 | 0.136138 | 0.157831 | 0.141979 | 0.141979 | 0.146936 | 0.101601 | 0.084702 |
| 0.128445 | 0.153668 | 0.168138 | 0.159416 | 0.159416 | 0.163051 | 0.10976 | 0.095143 |
| 0.151491 | 0.173456 | 0.179119 | 0.178995 | 0.178995 | 0.180932 | 0.118575 | 0.106872 |
| 0.166844 | 0.186192 | 0.185872 | 0.191544 | 0.191544 | 0.192288 | 0.124055 | 0.114392 |
| 0.178672 | 0.195791 | 0.190817 | 0.200978 | 0.200978 | 0.200775 | 0.128097 | 0.120047 |
| 0.188421 | 0.203577 | 0.194743 | 0.208614 | 0.208614 | 0.207615 | 0.131322 | 0.124624 |
| 0.19678 | 0.210167 | 0.198011 | 0.215068 | 0.215068 | 0.213376 | 0.134018 | 0.128494 |
| 0.204136 | 0.215906 | 0.200816 | 0.220681 | 0.220681 | 0.218372 | 0.13634 | 0.131859 |
| 0.21073 | 0.221003 | 0.203278 | 0.225661 | 0.225661 | 0.222794 | 0.138384 | 0.134845 |
| 0.216723 | 0.225599 | 0.205476 | 0.230147 | 0.230147 | 0.226769 | 0.140212 | 0.137536 |
| 0.222228 | 0.229791 | 0.207461 | 0.234235 | 0.234235 | 0.230384 | 0.141868 | 0.139987 |

| T 14 | T 15 | T 16 | T 17 | T 18 | T 19 | T 20 | T 21 |
|---|---|---|---|---|---|---|---|
| 0.21072 | 0.24469 | 0.26502 | 0.33579 | 0.52797 | 0.47796 | 0 | 0.0694 |
| 0.03534 | 0.02948 | 0.026556 | 0.0143 | 0.00475 | 0.0069 | 0.09715 | 0.06694 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0.00004 | 0.00004 |
| **$I$ m³/m** | | | | | | | |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.066438 | 0.061359 | 0.058744 | 0.039103 | 0.023099 | 0.028886 | 0.09795 | 0.083209 |
| 0.080589 | 0.07678 | 0.07489 | 0.05319 | 0.037471 | 0.04476 | 0.09915 | 0.08982 |
| 0.093262 | 0.090972 | 0.089992 | 0.06713 | 0.05403 | 0.06234 | 0.10115 | 0.096148 |
| 0.107929 | 0.107787 | 0.108139 | 0.084723 | 0.077906 | 0.086826 | 0.10515 | 0.104689 |
| 0.117556 | 0.119029 | 0.120406 | 0.09708 | 0.096503 | 0.105394 | 0.10915 | 0.111448 |
| 0.124903 | 0.12771 | 0.129945 | 0.106926 | 0.112332 | 0.120929 | 0.11315 | 0.117454 |
| 0.130916 | 0.134877 | 0.137862 | 0.115245 | 0.126377 | 0.134539 | 0.11715 | 0.123037 |
| 0.136044 | 0.141031 | 0.144687 | 0.122521 | 0.139147 | 0.146789 | 0.12115 | 0.128349 |
| 0.140535 | 0.146452 | 0.15072 | 0.12903 | 0.150945 | 0.158013 | 0.12515 | 0.133472 |
| 0.144546 | 0.151316 | 0.156149 | 0.134947 | 0.161971 | 0.168426 | 0.12915 | 0.138454 |
| 0.148178 | 0.15574 | 0.1611 | 0.140392 | 0.172363 | 0.17818 | 0.13315 | 0.143327 |
| 0.151505 | 0.159808 | 0.165662 | 0.145447 | 0.182223 | 0.187383 | 0.13715 | 0.148115 |

| T 22 | T 23 | T 24 | T 25 | T 26 | T 27 |
|---|---|---|---|---|---|
| 0.11976 | 0.0928 | 0 | 0 | 0.16217 | 0.1314 |
| 0.07564 | 0.08696 | 0.10032 | 0.12879 | 0.0638 | 0.07258 |
| 0 | 0 | 0.00008 | 0.00006 | 0 | 0 |
| **$I$ m³/m** | | | | | |
| 0 | 0 | 0 | 0 | 0 | 0 |
| 0.108284 | 0.11483 | 0.10192 | 0.12999 | 0.103707 | 0.10759 |
| 0.120843 | 0.125021 | 0.10432 | 0.13179 | 0.120321 | 0.121356 |
| 0.131302 | 0.133327 | 0.10832 | 0.13479 | 0.134636 | 0.132928 |
| 0.142667 | 0.142185 | 0.11632 | 0.14079 | 0.150653 | 0.145604 |
| 0.149765 | 0.147637 | 0.12432 | 0.14679 | 0.160892 | 0.153572 |
| 0.155015 | 0.151632 | 0.13232 | 0.15279 | 0.168576 | 0.159488 |
| 0.159214 | 0.154805 | 0.14032 | 0.15879 | 0.174788 | 0.164233 |
| 0.162728 | 0.157446 | 0.14832 | 0.16479 | 0.180034 | 0.168216 |
| 0.16576 | 0.159715 | 0.15632 | 0.17079 | 0.184591 | 0.171658 |
| 0.168432 | 0.161706 | 0.16432 | 0.17679 | 0.188632 | 0.174696 |
| 0.170825 | 0.163483 | 0.17232 | 0.18279 | 0.192269 | 0.177421 |
| 0.172994 | 0.16509 | 0.18032 | 0.18879 | 0.195583 | 0.179894 |

**Table B.2 INFILT infiltration parameters and actual cumulative infiltration for field C**

| Actual/ INFILT Values | | C1 | C2 | C3 | C 4 | C 5 |
|---|---|---|---|---|---|---|
| *a* | ------- | 0.61829 | 0.73773 | 0.60514 | 0.51408 | 0.39465 |
| *k* | m^3/min^a/m | 0.00129 | 0.00078 | 0.00178 | 0.00369 | 0.03901 |
| *fo* | m^3/min/m | 0 | 0 | 0 | 0 | 0.00021 |
| | | | | | | |
| ***t*(min)** | | ***I* m³/m** | | | | |
| 0 | | 0 | 0 | 0 | 0 | 0 |
| 15 | | 0.006883 | 0.005751 | 0.009165 | 0.014847 | 0.116735 |
| 50 | | 0.014489 | 0.013979 | 0.01899 | 0.02757 | 0.193173 |
| 75 | | 0.018617 | 0.018853 | 0.024271 | 0.033959 | 0.230122 |
| 100 | | 0.022242 | 0.023311 | 0.028887 | 0.039372 | 0.261146 |
| 150 | | 0.028579 | 0.031439 | 0.03692 | 0.048497 | 0.313319 |
| 200 | | 0.034142 | 0.038872 | 0.043941 | 0.056226 | 0.357702 |
| 250 | | 0.039193 | 0.045828 | 0.050293 | 0.063061 | 0.397265 |
| 350 | | 0.048257 | 0.058739 | 0.061651 | 0.074969 | 0.467224 |
| 400 | | 0.05241 | 0.06482 | 0.066839 | 0.080296 | 0.499029 |
| 450 | | 0.05637 | 0.070705 | 0.071777 | 0.085308 | 0.529277 |
| 600 | | 0.067343 | 0.087422 | 0.085426 | 0.098905 | 0.61305 |

| C 6 | C 7 | C 8 | C 9 | C 10 | C 11 | C 12 |
|---|---|---|---|---|---|---|
| 0 | 0.38079 | 0.2295 | 0.30041 | 0.2885 | 0.20835 | 0.10245 |
| 0.15275 | 0.02058 | 0.04427 | 0.01997 | 0.04525 | 0.06434 | 0.03173 |
| 0.00117 | 0 | 0 | 0.00021 | 0.00032 | 0.00064 | 0 |
| | | | | | | |
| ***I* m³/m** | | | | | | |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.14445 | 0.057715 | 0.082418 | 0.048199 | 0.103637 | 0.122715 | 0.041876 |
| 0.21125 | 0.091284 | 0.108648 | 0.075179 | 0.155885 | 0.177366 | 0.047373 |
| 0.2405 | 0.106525 | 0.119244 | 0.088808 | 0.181244 | 0.206179 | 0.049382 |
| 0.26975 | 0.118857 | 0.127382 | 0.100652 | 0.202851 | 0.23195 | 0.050859 |
| 0.32825 | 0.138701 | 0.139805 | 0.12147 | 0.240053 | 0.278755 | 0.053016 |
| 0.38675 | 0.154759 | 0.149347 | 0.140091 | 0.272673 | 0.322044 | 0.054602 |
| 0.44525 | 0.168483 | 0.157194 | 0.157392 | 0.302548 | 0.363279 | 0.055865 |
| 0.56225 | 0.191514 | 0.169814 | 0.189549 | 0.357235 | 0.442041 | 0.057824 |
| 0.62075 | 0.201504 | 0.175098 | 0.204799 | 0.382867 | 0.480192 | 0.058621 |
| 0.67925 | 0.210747 | 0.179896 | 0.21965 | 0.407676 | 0.517762 | 0.059332 |
| 0.85475 | 0.235146 | 0.192174 | 0.262447 | 0.478494 | 0.627955 | 0.061107 |

| C 13 | C 14 | C 15 | C 16 | C 17 |
|---|---|---|---|---|
| 0.79518 | 0.34353 | 0.18678 | 0.22346 | 0.24068 |
| 0.00155 | 0.04353 | 0.08068 | 0.06392 | 0.05756 |
| 0 | 0 | 0 | 0 | 0 |
| | | | | |
| ***I* m³/m** | | | | |
| 0 | 0 | 0 | 0 | 0 |
| 0.013352 | 0.11036 | 0.133794 | 0.11707 | 0.110454 |
| 0.034779 | 0.166892 | 0.167533 | 0.153211 | 0.14758 |
| 0.048011 | 0.191835 | 0.180713 | 0.167741 | 0.162709 |
| 0.060352 | 0.211762 | 0.190689 | 0.178878 | 0.174374 |
| 0.083314 | 0.243412 | 0.205691 | 0.195842 | 0.192248 |
| 0.104728 | 0.268696 | 0.217046 | 0.208845 | 0.206031 |
| 0.125062 | 0.290104 | 0.226284 | 0.219523 | 0.217399 |
| 0.163427 | 0.325651 | 0.240961 | 0.236665 | 0.235737 |
| 0.181735 | 0.340937 | 0.247046 | 0.243833 | 0.243436 |
| 0.199578 | 0.355015 | 0.252542 | 0.250336 | 0.250436 |
| 0.250878 | 0.391893 | 0.266483 | 0.266958 | 0.26839 |

**Table B.3 Scaling factors and scaled cumulative infiltration for field T (T11 selected as model curve).**

| **T-11 model curve Values** | |
|---|---|
| *a* | 0.15013 |
| *k* | 0.08167 |
| *fo* | 0 |
| *r* | 0.87942 |
| *dely* | 0.77 |
| *delz* | 0.87784168 |

| | | **T 1** | **T 2** | **T 3** | **T 4** | **T 5** |
|---|---|---|---|---|---|---|
| *Q* | m^3/min | 0.3036 | 0.3036 | 0.3036 | 0.3036 | 0.3378 |
| *Ao* | m^2 | 0.05 | 0.0262 | 0.05 | 0.05 | 0.0262 |
| *x* | m | 840 | 280 | 280 | 840 | 560 |
| *t* | min | 508 | 168 | 168 | 470 | 307 |
| | | | | | | |
| | | **T 1** | **T 2** | **T 3** | **T 4** | **T 5** |
| | Scaling factor | 0.79428149 | 1.014972524 | 0.9284776 | 0.72754543 | 0.974192 |
| | *k* scaled | 0.064868969 | 0.082892806 | 0.0758288 | 0.05941864 | 0.079562 |
| | *fo* scaled | 0 | 0 | 0 | 0 | 0 |
| | | | | | | |
| ***t* min** | | ***I* m³/m** | $I = F\,(Kt^{a} + f_o t)$ | | | |
| 0 | | 0 | 0 | 0 | 0 | 0 |
| 20 | | 0.101709292 | 0.13406 | 0.1188934 | 0.09316361 | 0.124747 |
| 50 | | 0.116708736 | 0.15383 | 0.136427 | 0.10690279 | 0.143144 |
| 150 | | 0.137636487 | 0.170701 | 0.1608906 | 0.12607218 | 0.168812 |
| 200 | | 0.143711205 | 0.189421 | 0.1679916 | 0.13163649 | 0.176263 |
| 300 | | 0.152731006 | 0.20131 | 0.1785353 | 0.13989844 | 0.187326 |
| 350 | | 0.156306822 | 0.210195 | 0.1827153 | 0.14317382 | 0.191712 |
| 400 | | 0.159471935 | 0.217356 | 0.1864152 | 0.146073 | 0.195594 |
| 500 | | 0.164904826 | 0.223388 | 0.192766 | 0.15104941 | 0.202257 |
| 600 | | 0.169480933 | 0.228618 | 0.1981152 | 0.15524103 | 0.20787 |
| 800 | | 0.176961136 | 0.233247 | 0.2068592 | 0.16209274 | 0.217044 |
| 900 | | 0.180118128 | 0.237408 | 0.2105496 | 0.16498448 | 0.220916 |
| 1000 | | 0.182989849 | 0.241194 | 0.2139065 | 0.16761492 | 0.224438 |

| T 6 | T 7 | T 8 | T 9 | T 10 | T 11 | T 12 | T 13 |
|---|---|---|---|---|---|---|---|
| 0.3378 | 0.3546 | 0.3504 | 0.3504 | 0.3504 | 0.3504 | 0.3216 | 0.3216 |
| 0.0262 | 0.0262 | 0.0262 | 0.0262 | 0.0262 | 0.0262 | 0.0262 | 0.0262 |
| 840 | 560 | 840 | 560 | 560 | 560 | 840 | 560 |
| 417 | 287 | 476 | 297 | 307 | 298 | 351 | 190 |
| | | | | | | | |
| **T 6** | **T 7** | **T 8** | **T 9** | **T 10** | **T 11** | **T 12** | **T 13** |
| 0.831783 | 0.9635 | 0.986036 | 0.9829 | 1.01497252 | 0.9861212 | 0.660837 | 0.564301 |
| 0.067932 | 0.0787 | 0.08053 | 0.0803 | 0.08289281 | 0.0805365 | 0.053971 | 0.046086 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| ***I* m³/m** | | | | | | | |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.106511 | 0.1234 | 0.126264 | 0.1259 | 0.12996921 | 0.1262747 | 0.084621 | 0.07226 |
| 0.122219 | 0.1416 | 0.144884 | 0.1444 | 0.14913625 | 0.1448969 | 0.097101 | 0.082916 |
| 0.144135 | 0.167 | 0.170865 | 0.1703 | 0.17587877 | 0.1708793 | 0.114513 | 0.097784 |
| 0.150496 | 0.1743 | 0.178406 | 0.1778 | 0.18364135 | 0.1784212 | 0.119567 | 0.1021 |
| 0.159942 | 0.1853 | 0.189603 | 0.189 | 0.1951673 | 0.1896195 | 0.127071 | 0.108508 |
| 0.163687 | 0.1896 | 0.194042 | 0.1934 | 0.19973666 | 0.194059 | 0.130046 | 0.111049 |
| 0.167001 | 0.1934 | 0.197972 | 0.1973 | 0.2037812 | 0.1979886 | 0.13268 | 0.113297 |
| 0.172691 | 0.2 | 0.204716 | 0.2041 | 0.21072362 | 0.2047336 | 0.1372 | 0.117157 |
| 0.177483 | 0.2056 | 0.210397 | 0.2097 | 0.21657119 | 0.210415 | 0.141007 | 0.120408 |
| 0.185316 | 0.2147 | 0.219683 | 0.219 | 0.22612977 | 0.2197019 | 0.14723 | 0.125723 |
| 0.188622 | 0.2185 | 0.223602 | 0.2229 | 0.23016393 | 0.2236214 | 0.149857 | 0.127966 |
| 0.19163 | 0.222 | 0.227167 | 0.2264 | 0.23383356 | 0.2271867 | 0.152246 | 0.130006 |

| T 14 | T 15 | T 16 | T 17 | T 18 | T 19 | T 20 | T 21 |
|---|---|---|---|---|---|---|---|
| 0.3216 | 0.3216 | 0.3678 | 0.3678 | 0.3678 | 0.3678 | 0.2382 | 0.2382 |
| 0.0262 | 0.0262 | 0.0262 | 0.0262 | 0.0262 | 0.0262 | 0.0262 | 0.0262 |
| 560 | 560 | 560 | 840 | 840 | 840 | 560 | 560 |
| 188 | 190 | 155 | 199 | 211 | 192 | 289 | 278 |
| | | | | | | | |
| **T 14** | **T 15** | **T 16** | **T 17** | **T 18** | **T 19** | **T 20** | **T 21** |
| 0.557899 | 0.564301 | 0.53398 | 0.421898 | 0.513383 | 0.474386 | 0.612162 | 0.587701 |
| 0.045564 | 0.046086 | 0.04361 | 0.034456 | 0.041928 | 0.038743 | 0.049995 | 0.047998 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| ***I* m³/m** | | | | | | | |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.07144 | 0.07226 | 0.068377 | 0.054025 | 0.06574 | 0.060746 | 0.078389 | 0.075256 |
| 0.081976 | 0.082916 | 0.078461 | 0.061992 | 0.075435 | 0.069705 | 0.089949 | 0.086355 |
| 0.096675 | 0.097784 | 0.09253 | 0.073108 | 0.088961 | 0.082204 | 0.106078 | 0.101839 |
| 0.100942 | 0.1021 | 0.096614 | 0.076335 | 0.092888 | 0.085832 | 0.11076 | 0.106334 |
| 0.107277 | 0.108508 | 0.102678 | 0.081126 | 0.098718 | 0.091219 | 0.117712 | 0.113008 |
| 0.109789 | 0.111049 | 0.105082 | 0.083025 | 0.101029 | 0.093355 | 0.120467 | 0.115654 |
| 0.112012 | 0.113297 | 0.10721 | 0.084707 | 0.103075 | 0.095245 | 0.122907 | 0.117996 |
| 0.115828 | 0.117157 | 0.110862 | 0.087592 | 0.106586 | 0.09849 | 0.127094 | 0.122016 |
| 0.119042 | 0.120408 | 0.113939 | 0.090023 | 0.109544 | 0.101223 | 0.130621 | 0.125402 |
| 0.124297 | 0.125723 | 0.118967 | 0.093996 | 0.114379 | 0.10569 | 0.136386 | 0.130936 |
| 0.126514 | 0.127966 | 0.12109 | 0.095673 | 0.116419 | 0.107576 | 0.138819 | 0.133272 |
| 0.128531 | 0.130006 | 0.12302 | 0.097199 | 0.118275 | 0.109291 | 0.141032 | 0.135397 |

| T 22 | T 23 | T 24 | T 25 | T 26 | T 27 |
|---|---|---|---|---|---|
| 0.4122 | 0.4134 | 0.3462 | 0.4272 | 0.3876 | 0.3876 |
| 0.0262 | 0.0262 | 0.0262 | 0.0262 | 0.0262 | 0.0262 |
| 280 | 560 | 560 | 280 | 560 | 840 |
| 99 | 197 | 203 | 106 | 222 | 348 |
| | | | | | |
| **T 22** | **T 23** | **T 24** | **T 25** | **T 26** | **T 27** |
| 0.87861 | 0.790397 | 0.661641 | 0.980341 | 0.827342 | 0.81345 |
| 0.071756 | 0.064552 | 0.054036 | 0.080064 | 0.067569 | 0.066434 |
| 0 | 0 | 0 | 0 | 0 | 0 |
| | | | | | |
| ***I* m³/m** | | | | | |
| 0 | 0 | 0 | 0 | 0 | 0 |
| 0.112508 | 0.101212 | 0.084724 | 0.125535 | 0.105943 | 0.104164 |
| 0.1291 | 0.116138 | 0.097219 | 0.144048 | 0.121567 | 0.119525 |
| 0.152249 | 0.136963 | 0.114652 | 0.169878 | 0.143365 | 0.140958 |
| 0.158969 | 0.143008 | 0.119712 | 0.177375 | 0.149693 | 0.147179 |
| 0.168946 | 0.151984 | 0.127226 | 0.188508 | 0.159088 | 0.156417 |
| 0.172902 | 0.155542 | 0.130204 | 0.192922 | 0.162813 | 0.160079 |
| 0.176403 | 0.158692 | 0.132841 | 0.196828 | 0.16611 | 0.16332 |
| 0.182413 | 0.164098 | 0.137367 | 0.203534 | 0.171769 | 0.168884 |
| 0.187475 | 0.168652 | 0.141178 | 0.209182 | 0.176535 | 0.173571 |
| 0.195749 | 0.176096 | 0.14741 | 0.218414 | 0.184327 | 0.181232 |
| 0.199241 | 0.179237 | 0.150039 | 0.222311 | 0.187615 | 0.184465 |
| 0.202418 | 0.182095 | 0.152431 | 0.225855 | 0.190606 | 0.187406 |

**Table B.4 Scaling factors and scaled cumulative infiltration for field C (C5 selected as model curve)**

| C-5 model curve Values | |
|---|---|
| *a* | 0.39465 |
| *k* | 0.03901 |
| *fo* | 0.00021 |
| *r* | 0.91696 |
| *dely* | 0.77 |
| *delz* | 0.729284 |

| | | C 1 | C 2 | C 3 | C 4 | C 5 |
|---|---|---|---|---|---|---|
| *Q* | m^3/min | 0.0498 | 0.0498 | 0.0498 | 0.0498 | 0.3 |
| *Ao* | m^2 | 0.038 | 0.038 | 0.038 | 0.038 | 0.038 |
| *x* | m | 180 | 180 | 180 | 180 | 180 |
| *t* | min | 192 | 202 | 243 | 287 | 170 |
| | | | | | | |
| | | **C 1** | **C 2** | **C 3** | **C 4** | **C 5** |
| | Scaling factor | 0.096368905 | 0.105131 | 0.137948 | 0.168863 | 1.083208 |
| | *k* scaled | 0.003759351 | 0.004101 | 0.005381 | 0.006587 | 0.042256 |
| | $f_o$ scaled | 2.02375E-05 | 2.21E-05 | 2.9E-05 | 3.55E-05 | 0.000227 |
| | | | | | | |
| | ***t* min** | ***I* m³/m** | $I = F\,(Kt^a + f_o t)$ | | | |
| | 0 | 0 | 0 | 0 | 0 | 0 |
| | 15 | 0.013896841 | 0.01516 | 0.019893 | 0.024351 | 0.156204 |
| | 50 | 0.018615875 | 0.020308 | 0.026648 | 0.03262 | 0.209247 |
| | 75 | 0.022176644 | 0.024193 | 0.031745 | 0.038859 | 0.24927 |
| | 100 | 0.025166386 | 0.027455 | 0.036025 | 0.044098 | 0.282876 |
| | 150 | 0.030194215 | 0.03294 | 0.043222 | 0.052908 | 0.33939 |
| | 200 | 0.034471357 | 0.037606 | 0.049344 | 0.060403 | 0.387466 |
| | 250 | 0.038283978 | 0.041765 | 0.054802 | 0.067083 | 0.430321 |
| | 350 | 0.04502591 | 0.04912 | 0.064452 | 0.078897 | 0.506101 |
| | 400 | 0.048090923 | 0.052464 | 0.06884 | 0.084268 | 0.540553 |
| | 450 | 0.051005817 | 0.055643 | 0.073012 | 0.089375 | 0.573317 |
| | 600 | 0.059078935 | 0.064451 | 0.084569 | 0.103521 | 0.664061 |

| C 6 | C 7 | C 8 | C 9 | C 10 | C 11 | C 12 |
|---|---|---|---|---|---|---|
| 0.3 | 0.156 | 0.156 | 0.156 | 0.2244 | 0.4752 | 0.1134 |
| 0.038 | 0.038 | 0.038 | 0.038 | 0.038 | 0.038 | 0.038 |
| 180 | 180 | 180 | 180 | 180 | 180 | 180 |
| 179 | 165 | 169 | 135 | 186 | 72 | 122 |
| | | | | | | |
| **C 6** | **C 7** | **C 8** | **C 9** | **C 10** | **C 11** | **C 12** |
| 1.121216 | 0.49136 | 0.501 | 0.414 | 0.830029 | 0.99439 | 0.234717 |
| 0.043739 | 0.01917 | 0.02 | 0.0161 | 0.032379 | 0.038791 | 0.009156 |
| 0.000235 | 0.0001 | 1E-04 | 9E-05 | 0.000174 | 0.000209 | 4.93E-05 |
| | | | | | | |
| ***I* m³/m** | | | | | | |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.161685 | 0.07086 | 0.072 | 0.0597 | 0.119694 | 0.143396 | 0.033847 |
| 0.216589 | 0.09492 | 0.097 | 0.08 | 0.160339 | 0.192089 | 0.045341 |
| 0.258017 | 0.11307 | 0.115 | 0.0953 | 0.191008 | 0.228831 | 0.054014 |
| 0.292801 | 0.12832 | 0.131 | 0.1081 | 0.216759 | 0.259681 | 0.061295 |
| 0.351298 | 0.15395 | 0.157 | 0.1297 | 0.260064 | 0.311561 | 0.073541 |
| 0.401061 | 0.17576 | 0.179 | 0.1481 | 0.296903 | 0.355695 | 0.083959 |
| 0.44542 | 0.1952 | 0.199 | 0.1645 | 0.329741 | 0.395036 | 0.093245 |
| 0.52386 | 0.22958 | 0.234 | 0.1934 | 0.38781 | 0.464603 | 0.109666 |
| 0.55952 | 0.2452 | 0.25 | 0.2066 | 0.414209 | 0.49623 | 0.117131 |
| 0.593434 | 0.26007 | 0.265 | 0.2191 | 0.439315 | 0.526307 | 0.12423 |
| 0.687361 | 0.30123 | 0.307 | 0.2538 | 0.508849 | 0.60961 | 0.143893 |

| C 13 | C 14 | C 15 | C 16 | C 17 |
|---|---|---|---|---|
| 0.228 | 0.27 | 0.27 | 0.27 | 0.27 |
| 0.05 | 0.038 | 0.038 | 0.038 | 0.038 |
| 180 | 180 | 180 | 180 | 180 |
| 70 | 144 | 134 | 124 | 122 |
| | | | | |
| **C 13** | **C 14** | **C 15** | **C 16** | **C 17** |
| 0.31392 | 0.856541 | 0.812942 | 0.767445 | 0.758097 |
| 0.012246 | 0.033414 | 0.031713 | 0.029938 | 0.029573 |
| 6.59E-05 | 0.00018 | 0.000171 | 0.000161 | 0.000159 |
| | | | | |
| ***I*** **$m^3/m$** | | | | |
| 0 | 0 | 0 | 0 | 0 |
| 0.045269 | 0.123517 | 0.11723 | 0.110669 | 0.109321 |
| 0.060641 | 0.165461 | 0.157039 | 0.14825 | 0.146444 |
| 0.07224 | 0.197109 | 0.187076 | 0.176606 | 0.174455 |
| 0.081979 | 0.223682 | 0.212297 | 0.200416 | 0.197974 |
| 0.098357 | 0.268371 | 0.25471 | 0.240455 | 0.237526 |
| 0.11229 | 0.306386 | 0.290791 | 0.274517 | 0.271173 |
| 0.124709 | 0.340274 | 0.322953 | 0.304879 | 0.301165 |
| 0.146671 | 0.400197 | 0.379827 | 0.358569 | 0.354201 |
| 0.156655 | 0.427439 | 0.405682 | 0.382978 | 0.378313 |
| 0.16615 | 0.453347 | 0.430271 | 0.406191 | 0.401243 |
| 0.192448 | 0.525102 | 0.498374 | 0.470482 | 0.464751 |

**Table B.5 Coefficient of variation for the scaled and actual infiltration depths at various times up to advance time for field T**

| Time min | Scaled Infiltration depth $m^3/m$ | | | Actual Infiltration depth $m^3/m$ | | |
|---|---|---|---|---|---|---|
| | Stdve | Average AV1 | CV1 | Stdve | Average AV2 | CV2 |
| 50 | 0.029 | 0.111 | 0.258 | 0.034 | 0.109 | 0.317 |
| 100 | 0.032 | 0.123 | 0.258 | 0.034 | 0.120 | 0.281 |
| 200 | 0.035 | 0.136 | 0.258 | 0.033 | 0.134 | 0.246 |
| 300 | 0.037 | 0.145 | 0.258 | 0.032 | 0.144 | 0.225 |
| 400 | 0.039 | 0.151 | 0.258 | 0.032 | 0.152 | 0.210 |
| 500 | 0.040 | 0.156 | 0.258 | 0.031 | 0.158 | 0.199 |
| 600 | 0.041 | 0.161 | 0.258 | 0.031 | 0.164 | 0.190 |
| 700 | 0.042 | 0.165 | 0.258 | 0.031 | 0.169 | 0.184 |

(Where: Stdve is the standard deviation and CV is the coefficient of variation)

| Time min | AV1/AV2 | CV1-CV2 |
|---|---|---|
| 50 | 1.018 | -0.059 |
| 100 | 1.020 | -0.024 |
| 200 | 1.014 | 0.012 |
| 300 | 1.006 | 0.033 |
| 400 | 0.998 | 0.048 |
| 500 | 0.990 | 0.059 |
| 600 | 0.983 | 0.067 |
| 700 | 0.976 | 0.074 |

**Table B.6 Measured advance (*Mx*) and predicted advance (*Px*) data for field T**

| T1 | | | T2 | | | T3 | | |
|---|---|---|---|---|---|---|---|---|
| *Ta* (min) | *Mx* (m) | *Px* (m) | Ta | *Mx* | *Px* | *Ta* | *Mx* | *Px* |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 508 | 840 | 840 | 168 | 280 | 299.25 | 168 | 280 | 303.82 |
| 688 | 1120 | 1090.45 | 531 | 840 | 840 | 531 | 840 | 840 |
| **T4** | | | **T5** | | | **T6** | | |
| *Ta* | *Mx* | *Px* | *Ta* | *Mx* | *Px* | *Ta* | *Mx* | *Px* |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 131 | 280 | 256.94 | 131 | 280 | 260.06 | 110 | 280 | 253.57 |
| 307 | 560 | 560 | 307 | 560 | 560 | 417 | 840 | 840 |
| 470 | 840 | 817.91 | 470 | 840 | 811.97 | 615 | 1120 | 1171.5 |
| 635 | 1120 | 1061.9 | 635 | 1120 | 1048 | | | |
| **T7** | | | **T8** | | | **T9** | | |
| *Ta* | *Mx* | *Px* | *Ta* | *Mx* | *Px* | *Ta* | *Mx* | *Px* |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 123 | 280 | 260.56 | 144 | 280 | 290.19 | 297 | 560 | 560 |
| 287 | 560 | 560 | 476 | 840 | 840 | 484 | 840 | 857.39 |
| 457 | 840 | 841.4 | | | | 673 | 1120 | 1132.6 |
| **T10** | | | **T11** | | | **T12** | | |
| *Ta* | *Mx* | *Px* | *Ta* | *Mx* | *Px* | *Ta* | *Mx* | *Px* |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 132 | 280 | 261.98 | 131 | 280 | 267.0266 | 216 | 540 | 544.16 |
| 307 | 560 | 560 | 298 | 560 | 560 | 351 | 840 | 840 |
| 520 | 840 | 885.08 | 506 | 840 | 887.961 | 483 | 1120 | 1110.3 |
| 667 | 1120 | 1091.4 | 662 | 1120 | 1113.867 | | | |
| **T13** | | | **T14** | | | **T15** | | |
| *Ta* | *Mx* | *Px* | *Ta* | *Mx* | *Px* | *Ta* | *Mx* | *Px* |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 92 | 280 | 287.33 | 87 | 280 | 275.41 | 78 | 280 | 246.48 |
| 190 | 560 | 560 | 188 | 560 | 560 | 190 | 560 | 560 |
| 316 | 840 | 886.04 | 314 | 840 | 889.67 | 310 | 840 | 871.02 |
| | | | 446 | 1120 | 1212.8 | 448 | 1120 | 1205.6 |
| **T16** | | | **T17** | | | **T18** | | |
| *Ta* | *Mx* | *Px* | *Ta* | *Mx* | *Px* | *Ta* | *Mx* | *Px* |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 69 | 280 | 264.67 | 50 | 280 | 269.53 | 96 | 560 | 560 |
| 155 | 560 | 560 | 109 | 560 | 560 | 211 | 840 | 1165.4 |
| 258 | 840 | 890.43 | 199 | 840 | 978.14 | | | |
| 383 | 1120 | 1267 | | | | | | |

| T19 | | | T20 | | | T21 | | |
|---|---|---|---|---|---|---|---|---|
| ***Ta*** | ***Mx*** | ***Px*** | ***Ta*** | ***Mx*** | ***Px*** | ***Ta*** | ***Mx*** | ***Px*** |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 104 | 560 | 560 | 144 | 280 | 297.79 | 131 | 280 | 282.5099 |
| 192 | 840 | 989.61 | 289 | 560 | 560 | 278 | 560 | 560 |
| | | | 616 | 1120 | 1084.3 | 612 | 1120 | 1117.13 |
| **T22** | | | **T23** | | | **T24** | | |
| ***Ta*** | ***Mx*** | ***Px*** | ***Ta*** | ***Mx*** | ***Px*** | ***Ta*** | ***Mx*** | ***Px*** |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 99 | 280 | 298.52 | 106 | 280 | 317.93 | 110 | 280 | 319.69 |
| 197 | 560 | 560 | 197 | 560 | 560 | 203 | 560 | 560 |
| 315 | 840 | 852.77 | 314 | 840 | 850.36 | 325 | 840 | 854.28 |
| 440 | 1120 | 1143.187 | 439 | 1120 | 1140.888 | 455 | 1120 | 1147.931 |
| **T25** | | | **T26** | | | **T27** | | |
| ***Ta*** | ***Mx*** | ***Px*** | ***Ta*** | ***Mx*** | ***Px*** | ***Ta*** | ***Mx*** | ***Px*** |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 106 | 280 | 319.47 | 222 | 560 | 560 | 348 | 840 | 840 |
| 196 | 560 | 560 | 498 | 1120 | 1141.3 | 481 | 1120 | 1113.5 |
| 312 | 840 | 849.28 | | | | | | |

Where (*Ta*) is the advance time in minutes, (*Mx*) and (*Px*) are the measured and predicted advances in meters.

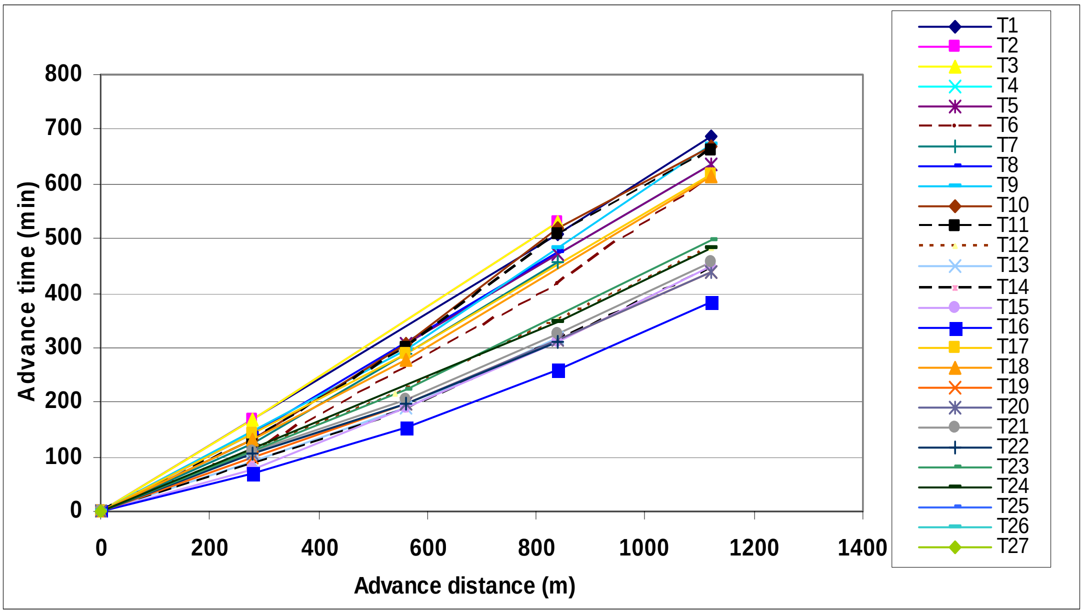
**Table B.7 Measured advance data for field C.**

| C1 | | C2 | | C3 | | C4 | |
|---|---|---|---|---|---|---|---|
| **T (min)** | **x (m)** | **T (min)** | **x (m)** | **T (min)** | **x (m)** | **T (min)** | **x (m)** |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 30 | 60 | 41 | 60 | 28 | 60 | 53 | 60 |
| 116 | 120 | | | 134 | 120 | 163 | 120 |
| 192 | 180 | 202 | 180 | 243 | 180 | 287 | 180 |
| 273 | 240 | 307 | 240 | 336 | 240 | 427 | 240 |
| **C5** | | **C6** | | **C7** | | **C8** | |
| **T (min)** | **x (m)** | **T (min)** | **x (m)** | **T (min)** | **x (m)** | **T (min)** | **x (m)** |
| 30 | 60 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | 46 | 60 | 27 | 60 | 42 | 60 |
| 170 | 180 | 109 | 120 | 98 | 120 | 111 | 120 |
| 277 | 240 | 179 | 180 | 165 | 180 | 169 | 180 |
| | | 367 | 240 | 238 | 240 | 246 | 240 |
| **C9** | | **C10** | | **C11** | | **C12** | |
| **T (min)** | **x (m)** | **T (min)** | **x (m)** | **T (min)** | **x (m)** | **T (min)** | **x (m)** |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 30 | 60 | 38 | 60 | 17 | 60 | 35 | 60 |
| | | 101 | 120 | | | 81 | 120 |
| 135 | 180 | 186 | 180 | 72 | 180 | 122 | 180 |
| 210 | 240 | | | 109 | 240 | 164 | 240 |
| **C13** | | **C14** | | **C15** | | **C16** | |
| **T (min)** | **x (m)** | **T (min)** | **x (m)** | **T (min)** | **x (m)** | **T (min)** | **x (m)** |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 19 | 60 | 29 | 60 | 35 | 60 | 32 | 60 |
| 56 | 120 | 87 | 120 | 85 | 120 | 76 | 120 |
| 70 | 180 | 144 | 180 | 134 | 180 | 124 | 180 |
| 136 | 240 | | | 189 | 240 | | |
| **C17** | | | | | | | |
| **T (min)** | **x (m)** | | | | | | |
| 30 | 60 | | | | | | |
| 72 | 120 | | | | | | |
| 122 | 180 | | | | | | |
| 171 | 240 | | | | | | |

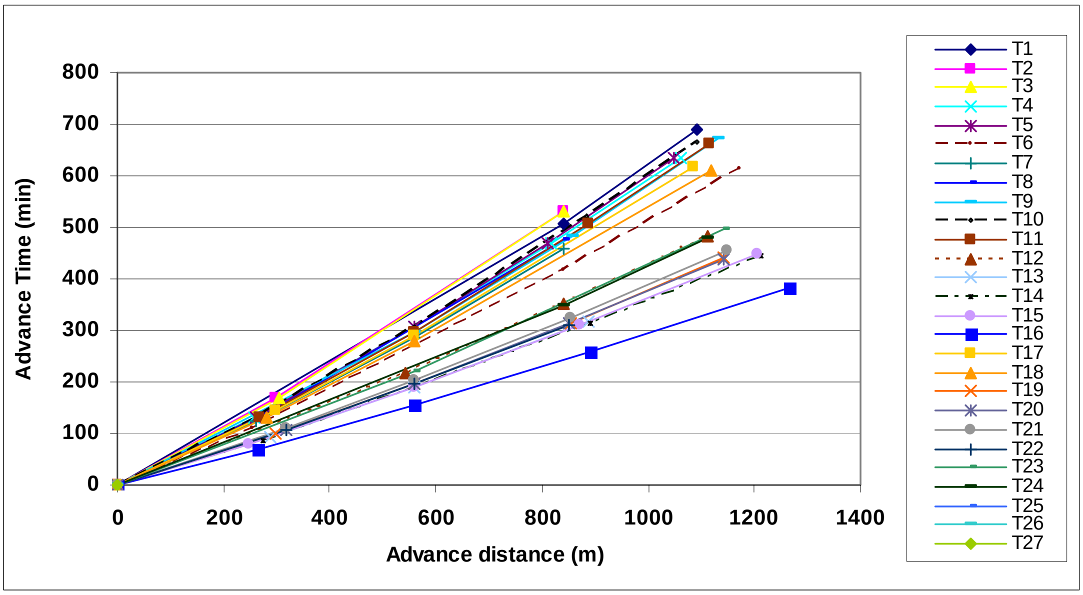
Where T is the measured time in minutes and X is the measured advance in meters.

**Table B.8 Power curve *p* & *r* values for fields T and C**

| Field T | | | Field C | | |
|---|---|---|---|---|---|
| | *r* | *p* | | *r* | *p* |
| T1 | 0.856 | 4.115 | C1 | 0.714 | 4.288 |
| T2 | 0.939 | 2.311 | C2 | 0.679 | 4.892 |
| T3 | 0.939 | 2.311 | C3 | 0.639 | 5.609 |
| T4 | 0.898 | 3.363 | C4 | 0.684 | 3.772 |
| T5 | 0.898 | 3.363 | C5 | 0.617 | 7.500 |
| T6 | 0.791 | 7.019 | C6 | 0.686 | 7.763 |
| T7 | 0.833 | 5.094 | C7 | 0.694 | 5.284 |
| T8 | 0.911 | 3.044 | C8 | 0.808 | 2.806 |
| T9 | 0.826 | 5.116 | C9 | 0.693 | 5.918 |
| T10 | 0.855 | 4.184 | C10 | 0.678 | 5.199 |
| T11 | 0.850 | 4.398 | C11 | 0.730 | 7.853 |
| T12 | 0.887 | 4.640 | C12 | 0.832 | 1.961 |
| T13 | 0.853 | 6.222 | C13 | 0.643 | 14.990 |
| T14 | 0.816 | 7.709 | C14 | 0.703 | 5.385 |
| T15 | 0.799 | 8.549 | C15 | 0.850 | 2.786 |
| T16 | 0.777 | 11.073 | C16 | 0.808 | 4.651 |
| T17 | 0.751 | 15.875 | C17 | 0.800 | 3.901 |
| T18 | 0.765 | 14.910 | | | |
| T19 | 0.729 | 13.603 | | | |
| T20 | 0.927 | 2.906 | | | |
| T21 | 0.879 | 3.962 | | | |
| T22 | 0.884 | 5.178 | | | |
| T23 | 0.904 | 4.598 | | | |
| T24 | 0.905 | 4.436 | | | |
| T25 | 0.971 | 3.214 | | | |
| T26 | 0.841 | 6.035 | | | |
| T27 | 0.815 | 7.257 | | | |




(a) Measured




(b) Predicted

**Figure B.1 Measured and predicted advance curves for field T**

# APPENDIX C: Irrigation Performance Simulated Under Different Modelling Strategies for the Fields T and C

**Table C.1 Irrigation performance results simulated under strategies 1, 2 and 3 for Field T.**

| $E_a$ | $E_r$ | $E_a$ | $E_r$ | $E_a$ | $E_r$ |
|---|---|---|---|---|---|
| **Strategy-1** | | **Strategy-2** | | **Strategy-3** | |
| 58.36 | 100 | 58.36 | 100 | 90.88 | 99.98 |
| 76.85 | 86 | 84.61 | 93.12 | 91.32 | 84.01 |
| 85.68 | 91 | 89.16 | 96.06 | 92.01 | 88.98 |
| 50.12 | 100 | 50.12 | 100 | 66.8 | 98.78 |
| 86.16 | 97 | 86.21 | 97.51 | 96.81 | 93.61 |
| 77.11 | 98 | 78.72 | 99.28 | 97.31 | 94.11 |
| 54.11 | 90 | 54.55 | 92 | 71.51 | 99.91 |
| 79.11 | 100 | 78.75 | 99.32 | 83.91 | 99.3 |
| 78.11 | 99 | 78.74 | 99.31 | 96.92 | 95.38 |
| 72.71 | 92 | 77.71 | 98.62 | 95.01 | 85.21 |
| 79.49 | 98.19 | 75.52 | 95.83 | 86.11 | 89.11 |
| 80.96 | 92.59 | 75.09 | 95.3 | 81.11 | 84.11 |
| 77.35 | 50.32 | 74.36 | 50.02 | 87.01 | 83.01 |
| 65.36 | 66.36 | 65.36 | 60.75 | 95.11 | 88.11 |
| 65.37 | 65.94 | 62.38 | 65.87 | 91.02 | 84.01 |
| 78.01 | 81.01 | 84.46 | 86.1 | 81.28 | 69.24 |
| 91.48 | 93.46 | 93.46 | 95.08 | 94.86 | 91.71 |
| 93.42 | 91.56 | 93.37 | 91.51 | 98.21 | 90.81 |
| 84.64 | 77.68 | 92.48 | 82.94 | 98.51 | 77.07 |
| 85.9 | 90.51 | 82.23 | 87.1 | 97.05 | 91.77 |
| 82.31 | 99.51 | 81.67 | 98.74 | 92.31 | 96.99 |
| 82.11 | 99.28 | 81.78 | 98.87 | 97.07 | 96.66 |
| 53.42 | 100 | 53.37 | 99.47 | 88.22 | 90.85 |
| 84.66 | 77.65 | 92.45 | 82.95 | 98.52 | 77.06 |
| 85.7 | 90.52 | 82.24 | 87.11 | 97.06 | 91.76 |
| 82.32 | 99.52 | 81.62 | 98.75 | 92.32 | 96.98 |
| 82.14 | 99.29 | 81.79 | 98.88 | 97.12 | 96.64 |
| **76.7762963** | **89.8663** | **77.428148** | **90.758889** | **90.93963** | **90.191111** |

**Table: C.2 Irrigation performance results simulated under strategies 4a, and 4b for Field T**

| $E_a$ | $E_r$ | $E_a$ | $E_r$ |
|---|---|---|---|
| **Strategy-4a**** | | **strategy-4b**** | |
| 83.8 | 100 | 64.85 | 100 |
| 98.11 | 83.11 | 78.99 | 85.66 |
| 99.99 | 86.91 | 89.53 | 89.54 |
| 63.71 | 98.76 | 55.87 | 100 |
| 99.67 | 91.74 | 93.34 | 94.93 |
| 99.99 | 92.35 | 92.33 | 94.68 |
| 71.26 | 98.56 | 64.96 | 99.99 |
| 62.49 | 93.68 | 79.71 | 99.83 |
| 98.08 | 94.06 | 90.99 | 97.13 |
| 98.08 | 86.17 | 82.71 | 88.12 |
| 99.02 | 72.17 | 85.66 | 86.21 |
| 98.96 | 76.81 | 84.37 | 79.91 |
| 95.28 | 54.23 | 95.28 | 55.81 |
| 99.99 | 76.91 | 97.42 | 79.93 |
| 98.24 | 69.36 | 94.76 | 70.94 |
| 95.11 | 65.11 | 60.37 | 68.65 |
| 77.59 | 89.94 | 89.99 | 88.27 |
| 64.16 | 91.23 | 99.05 | 90.53 |
| 93.88 | 77.92 | 84.63 | 79.14 |
| 96.89 | 70.32 | 99.24 | 74.46 |
| 63.37 | 96.47 | 72.89 | 96.56 |
| 65.29 | 97.41 | 74.81 | 97.51 |
| 64.15 | 91.25 | 79.07 | 90.52 |
| 73.88 | 77.92 | 74.61 | 79.16 |
| 66.89 | 90.32 | 79.22 | 84.44 |
| 63.37 | 96.48 | 72.86 | 96.54 |
| 75.29 | 97.42 | 74.83 | 97.53 |
| **83.94592593** | **85.8004** | **81.939** | **87.6293** |

** The advance failed to reach the end of the field for six furrows in case of 4a and for four furrows in case of 4b.

**Table C.3 Irrigation performance results simulated under real time strategies 5 and 6 for Field T.**

| $E_a$ | $E_r$ | $E_a$ | $E_r$ |
|---|---|---|---|
| **Strategy-5** | | **Strategy-6** | |
| 87.7 | 98.7 | 89.34 | 100 |
| 78.87 | 88.7 | 80.33 | 85.84 |
| 86.02 | 97.61 | 80.6 | 91.46 |
| 66.13 | 99.85 | 65.36 | 98.68 |
| 91.61 | 95.48 | 91.65 | 95.52 |
| 91.26 | 95.88 | 90.87 | 95.48 |
| 65.37 | 99.32 | 65.48 | 99.96 |
| 88.37 | 96.56 | 89.13 | 97.39 |
| 89.98 | 96.05 | 91.54 | 97.71 |
| 88.32 | 94.1 | 83.87 | 89.36 |
| 76.7 | 85.8 | 71.39 | 84.51 |
| 71.24 | 92.77 | 69.25 | 90.17 |
| 82.25 | 65.11 | 82.22 | 68.95 |
| 82.82 | 83.23 | 84.56 | 86.93 |
| 80.56 | 79.75 | 82.56 | 81.2 |
| 82.22 | 77.24 | 78.77 | 75.92 |
| 91.22 | 95.84 | 93.65 | 93.47 |
| 91.26 | 95.88 | 96.97 | 93.47 |
| 87.55 | 81.57 | 88.66 | 82.38 |
| 87.93 | 97 | 85.68 | 94.52 |
| 84.31 | 97.91 | 85.53 | 99.32 |
| 87.94 | 97.26 | 88.94 | 98.37 |
| 71.26 | 95.86 | 76.97 | 93.45 |
| 77.52 | 81.55 | 78.65 | 82.36 |
| 87.92 | 97.3 | 85.66 | 94.54 |
| 84.34 | 97.92 | 85.56 | 99.33 |
| 87.92 | 97.28 | 88.92 | 98.36 |
| **83.281111** | **91.9081481** | **83.41148** | **91.431481** |

**Table C.4 Irrigation performance results simulated under strategies 1, 2 and 3 for Field C.**

| $E_a$ | $E_r$ | $E_a$ | $E_r$ | $E_a$ | $E_r$ |
|---|---|---|---|---|---|
| **Strategy-1** | | **strategy-2** | | **strategy-3** | |
| 44.42 | 77.23 | 36.7 | 63.98 | 81.53 | 75.71 |
| 48.18 | 99.98 | 40.56 | 96.73 | 85.98 | 95.96 |
| 55.19 | 94.89 | 51.28 | 88.6 | 83.18 | 90.98 |
| 57.6 | 99.24 | 57.95 | 99.6 | 85.5 | 93.51 |
| 16.55 | 100 | 16.55 | 100 | 40.37 | 100 |
| 16.43 | 100 | 16.43 | 100 | 37.92 | 99.98 |
| 23.32 | 100 | 23.32 | 100 | 82.82 | 93.77 |
| 23.32 | 100 | 23.32 | 100 | 92.43 | 98.5 |
| 23.32 | 100 | 23.32 | 100 | 74.13 | 91.24 |
| 42.78 | 100 | 42.78 | 100 | 63.98 | 99.64 |
| 57.55 | 100 | 57.55 | 100 | 94.85 | 99.97 |
| 52.04 | 94.26 | 55.21 | 100 | 90.27 | 85.38 |
| 27.46 | 100 | 27.46 | 100 | 80.33 | 93.72 |
| 43.91 | 98.79 | 43.85 | 98.67 | 59.67 | 99.94 |
| 44.45 | 100 | 44.46 | 100 | 53.24 | 100 |
| 44.44 | 100 | 44.44 | 100 | 58.24 | 99.32 |
| 44.44 | 100 | 44.44 | 100 | 61.53 | 98.86 |
| **39.14117647** | **97.9053** | **38.212941** | **96.91647059** | **72.11588235** | **95.08705882** |

**Table C.5 Irrigation performance results simulated under real time strategies 4a and 4b for Field C.**

| $E_a$ | $E_r$ | $E_a$ | $E_r$ |
|---|---|---|---|
| **Strategy-4a **** | | **Strategy-4b** | |
| 88.42 | 32 | 15.72 | 44.65 |
| 95.01 | 38.73 | 18.32 | 58.46 |
| 94.63 | 42.08 | 16.2 | 56.4 |
| 97.15 | 54.72 | 16.63 | 72.34 |
| 35.22 | 93.95 | 28.83 | 100 |
| 26.73 | 96.71 | 21.26 | 100 |
| 85.29 | 95.42 | 35.75 | 100 |
| 84.56 | 99.12 | 34.13 | 100 |
| 93.12 | 91.78 | 40.58 | 100 |
| 47.19 | 73.52 | 44.75 | 100 |
| 60.82 | 98.11 | 61.24 | 81.27 |
| 79.03 | 90.21 | 23.71 | 93.71 |
| 57.42 | 99.99 | 47.13 | 100 |
| 50.57 | 73.96 | 47.32 | 100 |
| 51.85 | 99.16 | 36.21 | 100 |
| 59.81 | 74.12 | 55.94 | 100 |
| 58.44 | 98.62 | 41.03 | 100 |
| **68.54470588** | **79.5412** | **34.397059** | **88.637059** |

**The advance failed to reach the end of the field for eight furrows

**Table C.6 Irrigation performance results simulated under real time strategies 5 and 6 for Field C.**

| $E_a$ | $E_r$ | $E_a$ | $E_r$ |
|---|---|---|---|
| **Strategy-5** | | **Strategy-6** | |
| 80.58 | 33.48 | 80.98 | 33.48 |
| 87.2 | 25.32 | 83.88 | 24.38 |
| 86.88 | 30.25 | 79.35 | 27.63 |
| 84.7 | 39.33 | 81.41 | 37.79 |
| 41.16 | 99.24 | 41.06 | 98.81 |
| 48.62 | 99.29 | 38.66 | 99.19 |
| 85.52 | 91.12 | 85.83 | 91.48 |
| 92.93 | 92.85 | 97.25 | 97.15 |
| 76.12 | 86.25 | 76.44 | 86.54 |
| 61.51 | 99.96 | 61.51 | 99.96 |
| 63.92 | 98.53 | 85.93 | 98.61 |
| 83.57 | 85.98 | 83.48 | 85.92 |
| 74.01 | 99.92 | 69.32 | 93.59 |
| 51.28 | 99.98 | 51.26 | 99.96 |
| 55.94 | 99.98 | 55.63 | 99.42 |
| 58.56 | 99.93 | 58.04 | 99.03 |
| 61.52 | 99.96 | 61.54 | 99.98 |
| **70.23647059** | **81.2570588** | **70.09235** | **80.76** |

**Table C.7 Total volume of water applied under strategy 1 for Field T.**

| Q (lps) | Tco (min) | Volume (m^3) |
|---|---|---|
| 5.06 | 889 | 269.9004 |
| 5.06 | 889 | 269.9004 |
| 5.63 | 740 | 249.972 |
| 5.63 | 740 | 249.972 |
| 5.91 | 740 | 262.404 |
| 5.84 | 837 | 293.2848 |
| 5.84 | 837 | 293.2848 |
| 5.84 | 837 | 293.2848 |
| 5.84 | 837 | 293.2848 |
| 5.36 | 650 | 209.04 |
| 5.36 | 650 | 209.04 |
| 5.36 | 650 | 209.04 |
| 6.13 | 380 | 139.764 |
| 6.13 | 380 | 139.764 |
| 6.13 | 380 | 139.764 |
| 3.97 | 816 | 194.3712 |
| 6.87 | 463 | 190.8486 |
| 6.89 | 447 | 184.7898 |
| 5.77 | 441 | 152.6742 |
| 7.12 | 413 | 176.4336 |
| 6.46 | 554 | 214.7304 |
| 6.46 | 554 | 214.7304 |
| 6.89 | 447 | 184.7898 |
| 5.77 | 441 | 152.6742 |
| 7.12 | 413 | 176.4336 |
| 6.46 | 554 | 214.7304 |
| 6.46 | 554 | 214.7304 |
| **Total** | | **5793.6366** |

**Table C.8 Total volume of water applied under strategy 1 for Field C.**

| Q(lps) | Tco (min) | Volume (m^3) |
|---|---|---|
| 0.83 | 1161 | 57.8178 |
| 0.83 | 1161 | 57.8178 |
| 0.83 | 1161 | 57.8178 |
| 0.83 | 1161 | 57.8178 |
| 5 | 559 | 167.7 |
| 5 | 559 | 167.7 |
| 2.6 | 807 | 125.892 |
| 2.6 | 807 | 125.892 |
| 2.6 | 807 | 125.892 |
| 2.6 | 807 | 125.892 |
| 2.6 | 807 | 125.892 |
| 1.89 | 230 | 26.082 |
| 3.8 | 231 | 52.668 |
| 4.5 | 200 | 54 |
| 4.5 | 200 | 54 |
| 4.5 | 200 | 54 |
| 4.5 | 200 | 54 |
| **Total** | | **1490.8812** |

**Table C.9 Total volume of water applied under strategy 6 for Field C.**

| Q(lps) | Tco (min) | Volume (m^3) |
|---|---|---|
| 6.5 | 25 | 9.75 |
| 6.5 | 25 | 9.75 |
| 6.5 | 30 | 11.7 |
| 6.5 | 40 | 15.6 |
| 6.5 | 170 | 66.3 |
| 6.5 | 180 | 70.2 |
| 6.5 | 80 | 31.2 |
| 6.5 | 75 | 29.25 |
| 6.5 | 85 | 33.15 |
| 6.5 | 120 | 46.8 |
| 6.5 | 139 | 54.21 |
| 6.5 | 38 | 14.82 |
| 6.5 | 70 | 27.3 |
| 6.5 | 120 | 46.8 |
| 6.5 | 110 | 42.9 |
| 6.5 | 105 | 40.95 |
| 6.5 | 100 | 39 |
| **Total** | | **589.68** |