AN INTEGRATED NUMERICAL MODEL FOR THE DESIGN AND MANAGEMENT OF FURROW IRRIGATION

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ABSTRACT FIDO (Furrow Irrigation Design Optimiser) is a decision support system for the design and management of furrow irrigation. It integrates an optimisation engine with a proven hydrodynamic simulation-model to allow automatic determination of design and management parameters as well as prediction of infiltration and roughness parameters. The package contains a database from which seasonal trends and variations in performance can be monitored.

KEYWORDS decision support system; furrow irrigation; hydrodynamic model; optimisation; simulation

1 Introduction

The practice of furrow irrigation has traditionally been based upon experience gained through experimentation over many seasons. Throughout the world, management and design remain primitive due to limitations of existing distribution systems, an absence of field measurement, a lack of proper training and a reluctance to change established techniques. Irrigations are often inefficient with losses occurring due to tailwater runoff and deep percolation.

Irrigation simulation software provides an accessible tool to both educate the irrigator and to optimise management and design practices. However, this technology is yet to be adopted at the farm level (Raine and Walker, 1998) with even the most recent simulation-models suffering from complex operation, unreliability, and an excess of input data requirements leading to extensive field measurement. They also only perform the primary task of simulating a single irrigation event, requiring the operator to determine an optimum design through repeated trial simulations.

FIDO (Furrow Irrigation Design Optimiser) is a decision support system (DSS) for furrow irrigation designed to automate the process of determining an optimum design or management strategy given a minimum of input data. An optimisation engine has been integrated with the simulation-model to both determine the design and management parameters and to calibrate the model. The input data requirements are minimised through calibration by estimating the semi-empirical infiltration parameters and/or the Manning *n* from more readily measured field-variables such as irrigation advance and/or runoff. FIDO also incorporates a database allowing seasonal trends and variations in performance to be monitored. This paper describes the ongoing development of the DSS.

2 Program Development

The primary goal of the FIDO project is to develop an easily used, reliable and flexible DSS for furrow irrigation that retains the accuracy of existing simulation-models while overcoming their limitations. The DSS is aimed at both irrigators and researchers and incorporates two levels of operation; one permitting the user access to only basic database facilities and one-touch design and management options; and another allowing complete control over model behaviour with extensive parameter analysis capabilities.

The objectives outlined in the development of FIDO include:

- accurate simulation of all phases of an irrigation event under a range of design and management conditions;
- the ability to calibrate the model using a range of parameters and input data so as to minimise field measurement requirements;
- the ability to automatically determine the optimum design or management strategy for a range of parameters and objective functions;
- robustness of the DSS for all simulation, calibration and optimisation operations;
- inclusion of a response surface generator for any combination of two parameters and objective function;
- inclusion of a relational database to allow seasonal trends and variations to be monitored;
- a simple user interface only showing information relative to the current task; and
- extensive graphical output.

These objectives were achieved through the integration of the simulation-model, an optimisation engine, a database, and a simple graphical user interface (GUI). The DSS was written in c++ using an object-orientated framework for the Microsoft Windows™ operating system.

2.1 Simulation-Model

The FIDO simulation-model is based upon the complete one-dimensional hydrodynamic equations which are used in the two leading furrow irrigation software packages SIRMOD (Walker, 1998) and SRFR (USDA, 1997). Both of these programs have been widely tested and proven accurate under a range of irrigation management conditions (McClymont *et al*, 1996b, Maheshwari *et al*, 1993a,b). The hydrodynamic equations have traditionally been difficult to solve and kinematic-wave and zero-inertia approximations were preferred for their solution-speed and ease of use. However, recent advances in solution techniques and increased computing power have led to the full hydrodynamic equations being the preferred model. A “wetted-perimeter dependent” Kostiakov-Lewis infiltration equation is linked to the model to simulate subsurface water flows.

2.2 Optimisation Engine

To meet the objective of operational robustness, an optimisation engine was required which would remain stable in the event of a malfunction of the simulation-model. This task is suited to an algorithm that does not require the calculation of derivative functions, and one that does not base its current iteration estimates on the magnitude of that calculated during the previous iteration. A specialised algorithm (McClymont, 1996) was developed to meet this criteria using a "common sense" approach of "forcing" the objective function to decrease by changing the design parameters individually. This process can be thought of as undertaking several separate optimisations with a single design parameter in each. However, this process by itself is very slow. To increase the rate of convergence and to adopt the nature of a gradient search method, the routine follows up the individual changes with a "group" parameter change. This is undertaken by changing all of the parameters together in the direction of the resultant vector obtained from the sum of the individual parameter vectors (Fig.1). For example, the steps in the minimisation process for an objective function with two design parameters are:

1. Select initial values for the two parameters.
2. Change the first parameter until the objective function cannot be lowered any further.
3. Change the second parameter until the objective function cannot be lowered any further.
4. Change both parameters as a group in the direction of the sum of the vectors from steps (2) and (3) until the objective function cannot be lowered any further.
5. Repeat steps (2) to (4) until the optimum design parameters have been found.

This method has an advantage over traditional optimisation methods in that it is mathematically simple and forces the objective function to increase/decrease with the individual parameter changes. It calculates the current iteration estimates based only on whether the previous attempt at changing a parameter resulted in success or failure. If the simulation-model malfunctions, then the result is classed as a failure and is ignored and the next attempt commences. This method has been found to be reliable in multiple parameter optimisation without user intervention (McClymont, 1996, McClymont *et al*, 1996a).

2.3 Irrigation Database

FIDO is designed around a relational database to allow for monitoring of seasonal trends and variations in performance, along with spatial and temporal variations of infiltration. Tables for the irrigation sites, events, inflow methods, furrow shapes, infiltration functions and field notes have been linked together using SQL to allow lookups and searches throughout the data. Calculated fields in the site database relating to seasonal performance are recalculated each time new event information is entered. The mean and standard deviation of infiltration variation of a site are also recalculated for each calibration event and used in calculating performance confidence intervals. The interface for the database (Fig.2) can be tailored to the user's needs.

2.4 Graphical User Interface

Operation of the model has been kept simple through use of a specially designed GUI. Features of the interface include:

- only information relevant to the current irrigation configuration will be displayed;
- separation of input data and results (Fig.3);
- single button operation of all major tasks;
- a range of parameter units are available for each dimensional variable;
- results including inflow/outflow hydrographs, advance/recession curves, volume balance components, simulation errors and efficiency/uniformity values are presented graphically;
- parameter and convergence response surfaces, and numerical output of any parameter in time and space are available for advanced users; and
- an interactive animation of the simulation also exists allowing users to visualise performance during different stages of the irrigation.

3 DSS Operation

FIDO was designed as tool for management and design of furrow irrigation systems and for research into improved irrigation techniques. The following modes of operation are available:

- evaluation of the performance of an individual irrigation;
- calibration of infiltration and roughness parameters from measured advance and/or runoff data;
- optimisation of irrigation management based on assumed or measured infiltration values;
- optimisation of irrigation design and management based on spatial and temporal variation at a site;
- optimisation of irrigation management based on infiltration parameter values obtained in real time during an irrigation event;
- investigation of response surfaces for any combination of two parameters and objective function; and
- evaluation of the average irrigation performance of a field over time.

These tasks can be categorised into four main areas; irrigation evaluation, calibration and parameter estimation, design and management, and site analysis.

3.1 Irrigation Evaluation

There are four distinguishable phases during an irrigation event; advance, storage, depletion and recession. Simulation (Fig.4) involves solving the hydrodynamic equations for flow rate and flow area during each phase either on a predefined grid, or on a grid defined during the advance phase. Combinations of these phases and grid design along with the presence of two possible furrow-end conditions leads to many simulation configurations. Robust solution of all configurations is required for inclusion of the simulation-model into the optimisation process where physically unrealistic input data will be encountered.

The use of interpolation and generalised solution techniques in current hydrodynamic models can often lead to convergence problems. This is avoided in the FIDO simulation-model by tailoring solution techniques to each phase configuration. The use of exception handling also improves reliability allowing convergence problems to be identified and handled with a more appropriate grid structure or better initial parameter estimates. The tailoring of solution techniques to each phase also means that little modification is required to simulate alternate irrigation strategies such as surge and cutback irrigation.

The solution techniques used are based on the Preissmann double sweep technique. This is probably the most common method for solving the hydrodynamic equations. It is an implicit solution method that solves one row of grid-cells simultaneously for each time step. FIDO uses several variations of this technique. Like SIRMOD (Walker, 1998), FIDO can solve for the unknown advance distance using constant time steps as in the traditional Preissmann approach. However, it is possible to define the grid before the simulation begins and solve instead for the unknown advance times as is utilised by SRFR (USDA, 1997). Both of these methods result in coefficients being calculated in a forward sweep starting from the upstream cell before the model parameters can be calculated in a backwards sweep.

All existing models make approximations during the recession phase. Typically, the recession is defined when the depth of flow at a cell node is less than a designated tolerance value. However, it is not uncommon for the depth of flow to be negative before the recession flag is activated. This causes irregularities in the recession curve due to the true recession point not coinciding with the nodes on the solution grid. Although it may have little effect on the accuracy of performance results, the effect is more pronounced on the reliability of the solution technique with convergence problems occurring in extreme cases. FIDO adopts a shooting method to solve for the recession by including the time step as an independent parameter. The coupling of the shooting algorithm to the Preissmann technique allows direct solution of recession times at each node, alleviating stability problems.

Irrigation performance is described though the calculation of traditional measures including storage efficiency, application efficiency, and distribution uniformity. These parameters are monitored during the simulation along with individual volume balance components such as deep percolation and runoff. A volume balance error is also calculated.

3.2 Calibration and Parameter Estimation

Many simulation-models are specifically designed to solve the “inverse problem” where the simulation is manipulated to determine infiltration parameters from measured irrigation-front advance data. This alternate usage of the model is essentially a calibration technique, yet there are currently no hydrodynamic software packages available for both simulation and calibration. Infiltration is typically calculated using a simple volume balance model with these results being imported later into the more complex hydrodynamic model. However, this may cause misleading results due to the differences in model structure and the empirical nature of the inverse technique.

FIDO utilises optimisation to solve the “inverse problem” using the complete hydrodynamic model. The objective function is determined by the availability of input data and is defined as the sum of the square of the errors between the measured and predicted data. The model can be calibrated using advance data, runoff hydrograph data, or a combination of both. If runoff data are not available, then only the advance phases of the simulation are used in the calibration. If runoff data exists, then all phases of the simulation are included. Any of the three parameters of the Kostiakov-Lewis infiltration equation can be included in the optimisation along with the Manning *n* roughness coefficient. The flexibility of the optimisation algorithm allows easy selection/deselection of calibration parameters (Fig.5). Response surfaces (Fig.3) can also be generated to evaluate calibration performance.

3.3 Design and Management

The traditional approach to design and management using simulation-models is based on the maximisation of application efficiency, storage efficiency, and distribution uniformity. However, the objective function used in the FIDO optimisation can be varied depending on site constraints (e.g. soil characteristics, water availability) and management variables (e.g. agronomic limitations, labour requirements). FIDO breaks down the application efficiency parameter into runoff volume and deep percolation volume components to allow greater flexibility in objective function definition. For example, an irrigation system with tailwater recycling may require more emphasis on minimising deep percolation than runoff where as a system growing crops sensitive to water logging would more likely be optimised according to opportunity time and application efficiency. The objective function chosen will also be dependent on whether the user is optimising field design or management practices.

For irrigation management, the objective function is defined using a weighting system based on the user-specified order of preference of minimising runoff, minimising deep percolation, maximising storage, and maximising distribution uniformity:

$$ObjectiveFunction = Minimise\left(w_1 \frac{RV}{TV} + w_2 \frac{DPV}{TV} + w_3(1 - SE) + w_4(1 - DU)\right)$$

where w_1,w_2,w_3,w_4 are weighting coefficients, *RV* is runoff volume, *TV* is total volume, *DPV* is deep percolation volume, *SE* is storage efficiency and *DU* is distribution uniformity. Complete simulations must be undertaken to calculate the objective function.

The objective functions for irrigation design are yet to be mathematically defined. However, it is envisaged that they will be based upon maximising the range of management options available to achieve a minimum level of performance and will be a function of the infiltration variation at a site. The current version of FIDO uses the same objective function for both design and management.

The user has direct control over which design and management parameters are included in the optimisation. In the current version, management parameters include discharge, time to cutoff, and the required depth of infiltration. This will later be extended to include a function representing variable inflow. Design parameters in the current version of the program include field length, field slope and the required depth of infiltration. A function representing variable field-slope will be included in later versions. To further investigate the design and management parameters and their effect on irrigation performance, response surfaces can be generated for any combination of two independent parameters and objective function.

3.4 Site Analysis

The addition of the database to the DSS allows variations in performance and infiltration properties to be monitored throughout an irrigation season. When infiltration data are not available during the design of an event, an average infiltration function for the site can be used in the absence of a better estimate. Knowledge of the range of infiltration functions likely at a particular site also enables the user to design an event accompanied by a confidence interval showing possible variations in the result. This analysis is suitable for the construction of design and management charts based on high, low and average infiltration records at a site (Raine *et al*, 1997, 1998). Future versions of FIDO will generate these charts.

4 Progress

This paper has discussed the design criteria used in developing FIDO. While much of the DSS is complete, work is still being undertaken on simulation of the recession phases. Full optimisation facilities along with the ability to simulate variable inflow techniques such as surge and cutback irrigation are not yet operational. However, the calibration option in FIDO is working and is proving reliable.

The recession was found to be the most difficult phase to simulate using generalised techniques. Although modifications to the Preissmann technique have been made to solve directly for the recession, convergence is slow and unreliable. If this cannot be rectified, other solution techniques may need investigating. A temporary solution to this has been to adopt the approximation technique used in SIRMOD. Results from FIDO and SIRMOD are nearly identical which is expected since the hydraulic equations are the same. It is important to recognise that simulation results are dominated by the hydraulic model and grid definition rather than the solution techniques used.

5 References

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6 Figures

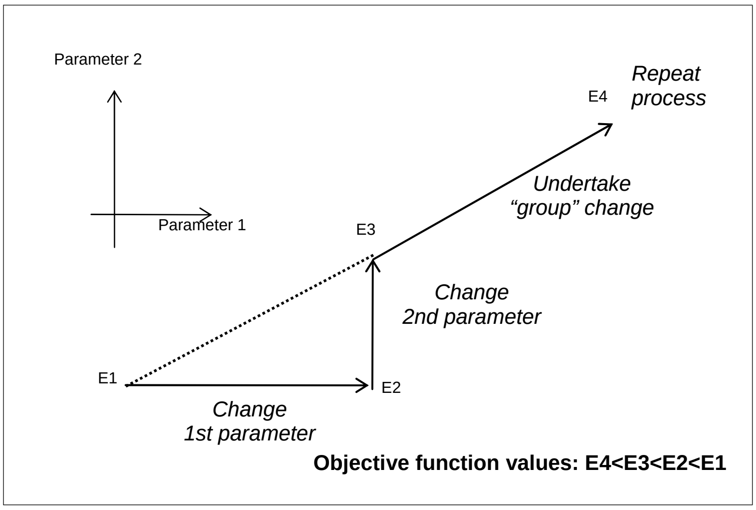
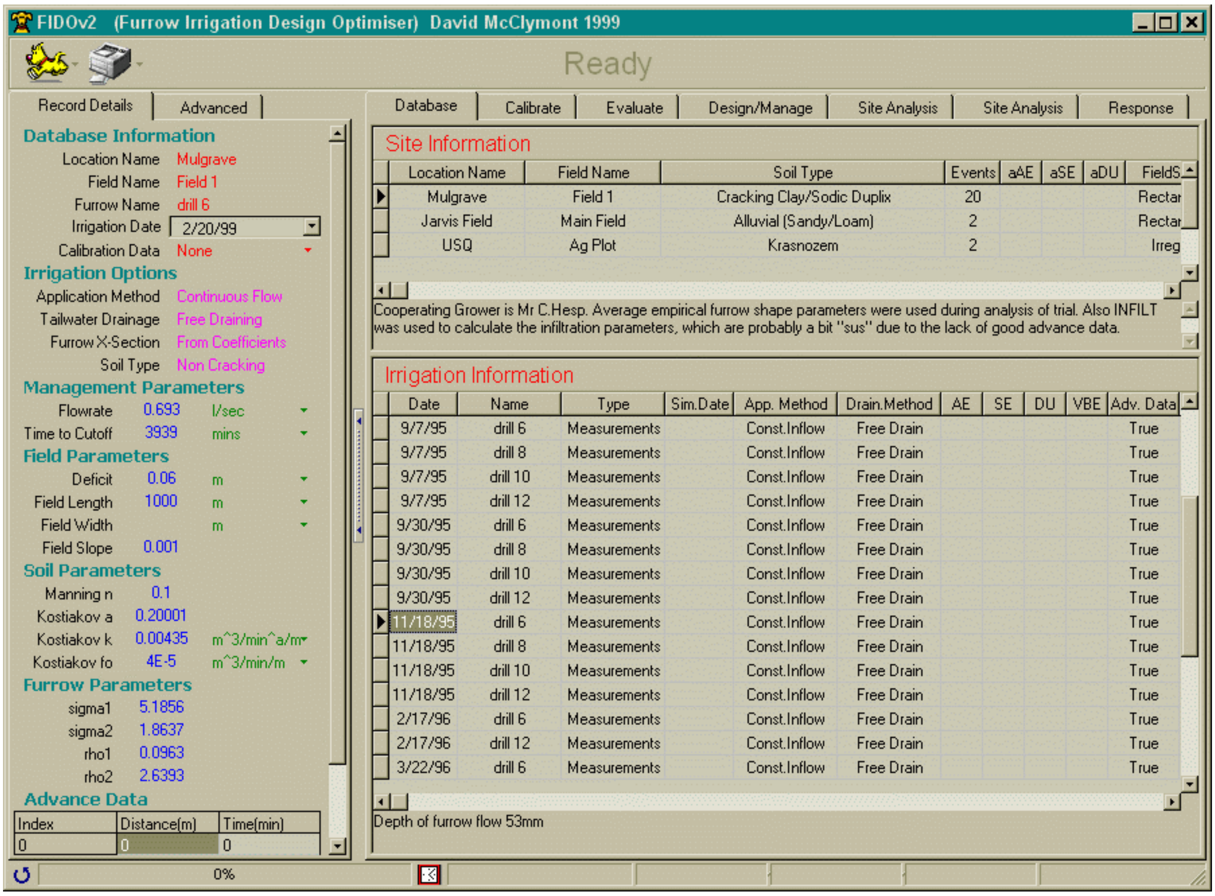


Fig.1 Optimisation step-cycle for two parameters.



Database Information
Location Name Mulgrave
Field Name Field 1
Furrow Name drill 6
Irrigation Date 2/20/99
Calibration Data None

Irrigation Options
Application Method Continuous Flow
Tailwater Drainage Free Draining
Furrow X-Section From Coefficients
Soil Type Non Cracking

Management Parameters
Flowrate 0.693 l/sec
Time to Cutoff 3939 mins

Field Parameters
Deficit 0.06 m
Field Length 1000 m
Field Width m
Field Slope 0.001

Soil Parameters
Manning n 0.1
Kostiakov a 0.20001
Kostiakov k 0.00435 m^3/min^a/m
Kostiakov fo 4E-5 m^3/min/m

Furrow Parameters
sigma1 5.1856
sigma2 1.8637
rho1 0.0963
rho2 2.6393

Advance Data

Index	Distance(m)	Time(min)
0	0	0

Site Information

Location Name	Field Name	Soil Type	Events	aAE	aSE	aDU	FieldS
Mulgrave	Field 1	Cracking Clay/Sodic Duplix	20				Rectar
Jarvis Field	Main Field	Alluvial (Sandy/Loam)	2				Rectar
USQ	Ag Plot	Krasnozem	2				Irreg

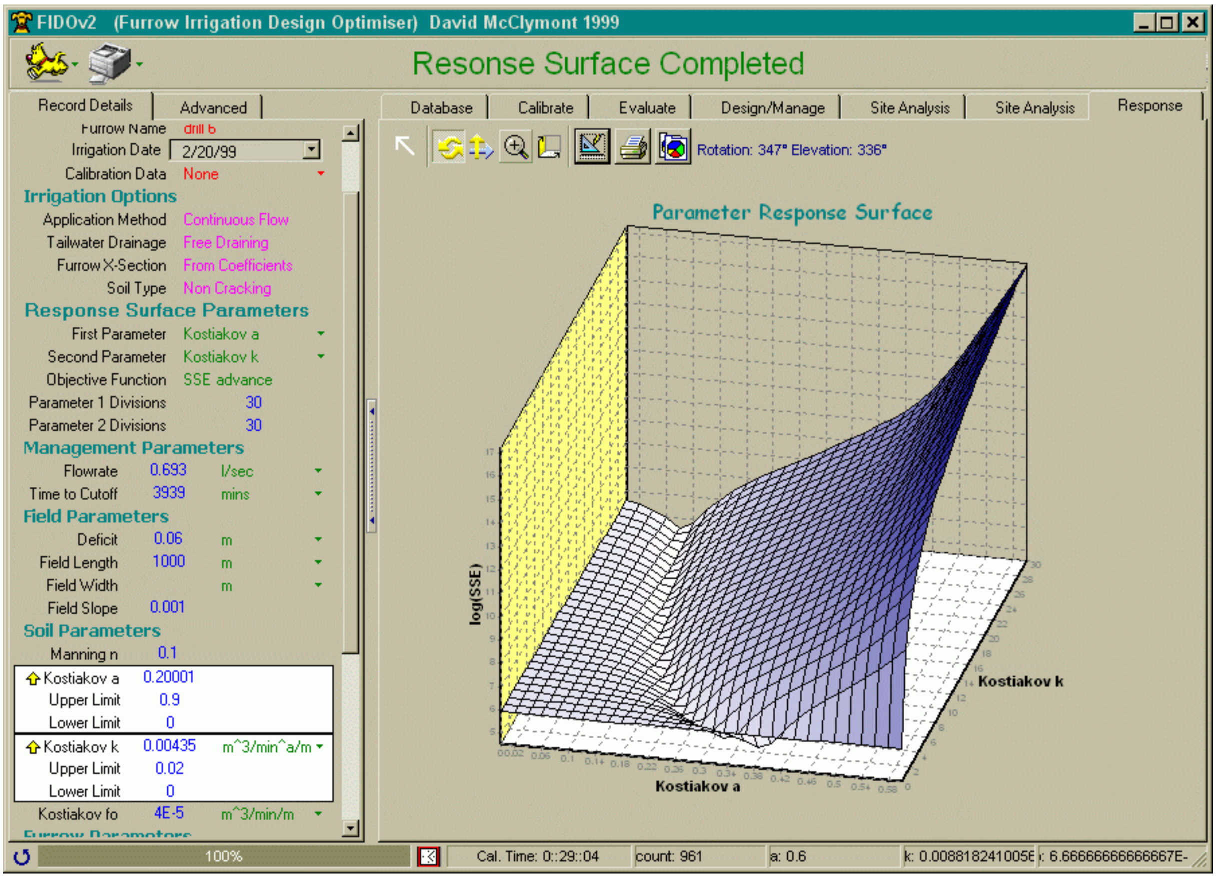
Cooperating Grower is Mr C.Hesp. Average empirical furrow shape parameters were used during analysis of trial. Also INFILT was used to calculate the infiltration parameters, which are probably a bit "sus" due to the lack of good advance data.

Irrigation Information

Date	Name	Type	Sim.Date	App. Method	Drain.Method	AE	SE	DU	VBE	Adv. Data
9/7/95	drill 6	Measurements		Const.Inflow	Free Drain					True
9/7/95	drill 8	Measurements		Const.Inflow	Free Drain					True
9/7/95	drill 10	Measurements		Const.Inflow	Free Drain					True
9/7/95	drill 12	Measurements		Const.Inflow	Free Drain					True
9/30/95	drill 6	Measurements		Const.Inflow	Free Drain					True
9/30/95	drill 8	Measurements		Const.Inflow	Free Drain					True
9/30/95	drill 10	Measurements		Const.Inflow	Free Drain					True
9/30/95	drill 12	Measurements		Const.Inflow	Free Drain					True
11/18/95	drill 6	Measurements		Const.Inflow	Free Drain					True
11/18/95	drill 8	Measurements		Const.Inflow	Free Drain					True
11/18/95	drill 10	Measurements		Const.Inflow	Free Drain					True
11/18/95	drill 12	Measurements		Const.Inflow	Free Drain					True
2/17/96	drill 6	Measurements		Const.Inflow	Free Drain					True
2/17/96	drill 12	Measurements		Const.Inflow	Free Drain					True
3/22/96	drill 6	Measurements		Const.Inflow	Free Drain					True

Depth of furrow flow 53mm

Fig. 2 FIDO database interface.



Resonse Surface Completed

Rotation: 347° Elevation: 336°

Furrow Name drill 6
Irrigation Date 2/20/99
Calibration Data None

Irrigation Options
Application Method Continuous Flow
Tailwater Drainage Free Draining
Furrow X-Section From Coefficients
Soil Type Non Cracking

Response Surface Parameters
First Parameter Kostiakov a
Second Parameter Kostiakov k
Objective Function SSE advance
Parameter 1 Divisions 30
Parameter 2 Divisions 30

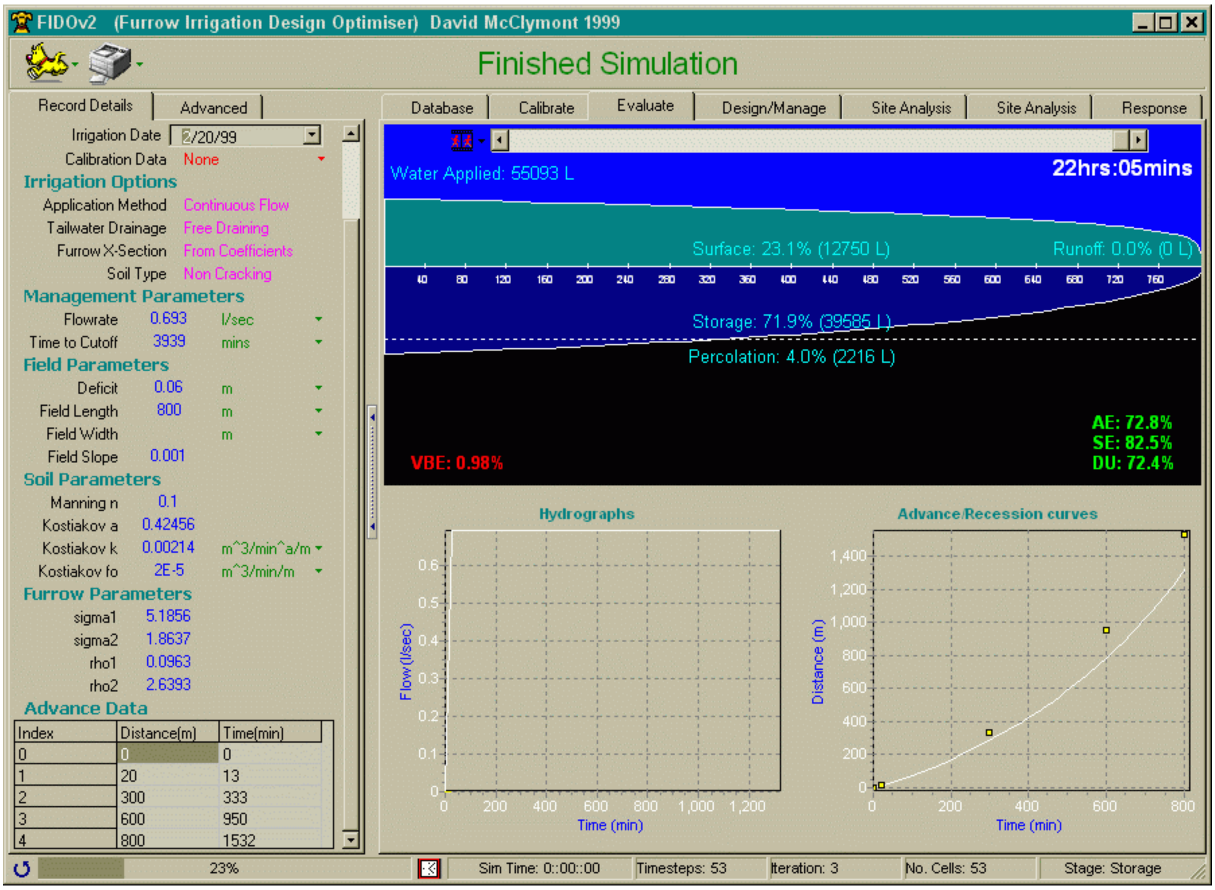
Management Parameters
Flowrate 0.693 l/sec
Time to Cutoff 3939 mins

Field Parameters
Deficit 0.06 m
Field Length 1000 m
Field Width m
Field Slope 0.001

Soil Parameters
Manning n 0.1
Kostiakov a 0.20001
Upper Limit 0.9
Lower Limit 0
Kostiakov k 0.00435 m^3/min^a/m
Upper Limit 0.02
Lower Limit 0
Kostiakov fo 4E-5 m^3/min/m

Cal. Time: 0::29::04 | count: 961 | a: 0.6 | k: 0.008818241005 | 6.66666666666667E-

Fig. 3 Example of the FIDO GUI showing separation of input data and results.



Finished Simulation

Water Applied: 55093 L
22hrs:05mins
Surface: 23.1% (12750 L)
Runoff: 0.0% (0 L)
Storage: 71.9% (39585 L)
Percolation: 4.0% (2216 L)
VBE: 0.98%
AE: 72.8%
SE: 82.5%
DU: 72.4%

Irrigation Date 2/20/99
Calibration Data None

Irrigation Options
Application Method Continuous Flow
Tailwater Drainage Free Draining
Furrow X-Section From Coefficients
Soil Type Non Cracking

Management Parameters
Flowrate 0.693 l/sec
Time to Cutoff 3939 mins

Field Parameters
Deficit 0.06 m
Field Length 800 m
Field Width m
Field Slope 0.001

Soil Parameters
Manning n 0.1
Kostiakov a 0.42456
Kostiakov k 0.00214 m^3/min^a/m
Kostiakov fo 2E-5 m^3/min/m

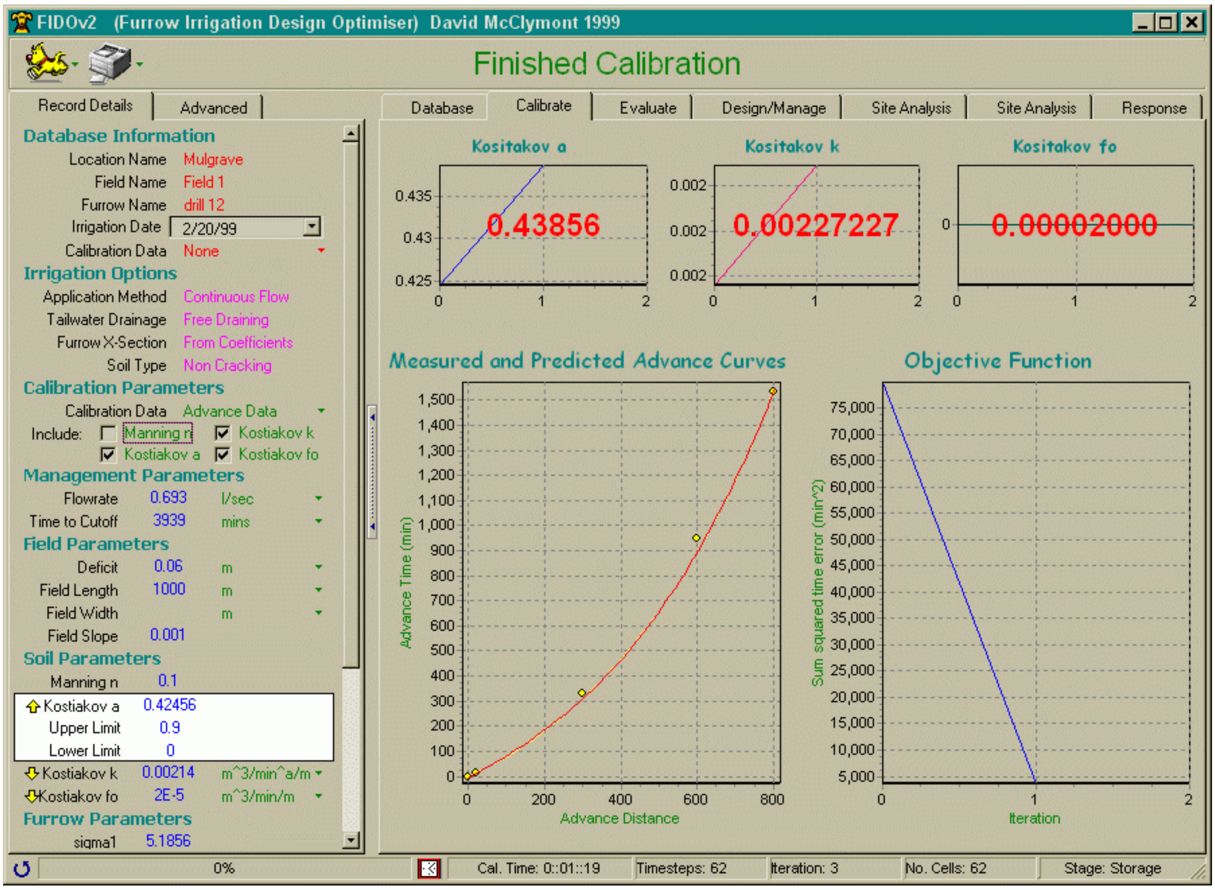
Furrow Parameters
sigma1 5.1856
sigma2 1.8637
rho1 0.0963
rho2 2.6393

Advance Data

Index	Distance(m)	Time(min)
0	0	0
1	20	13
2	300	333
3	600	950
4	800	1532

Sim Time: 0::00::00 | Timesteps: 53 | Iteration: 3 | No. Cells: 53 | Stage: Storage

Fig. 4 Evaluation screen in FIDO showing irrigation animation.



Database Information

Location Name Mulgrave
Field Name Field 1
Furrow Name drill 12
Irrigation Date 2/20/99
Calibration Data None

Irrigation Options

Application Method Continuous Flow
Tailwater Drainage Free Draining
Furrow X-Section From Coefficients
Soil Type Non Cracking

Calibration Parameters

Calibration Data Advance Data
Include: ☐ Manning n ☑ Kostiakov k
☑ Kostiakov a ☑ Kostiakov fo

Management Parameters

Flowrate 0.693 l/sec
Time to Cutoff 3939 mins

Field Parameters

Deficit 0.06 m
Field Length 1000 m
Field Width m
Field Slope 0.001

Soil Parameters

Manning n 0.1
Kostiakov a 0.42456
Upper Limit 0.9
Lower Limit 0
Kostiakov k 0.00214 m^3/min^a/m
Kostiakov fo 2E-5 m^3/min/m

Furrow Parameters

sigma1 5.1856

0% Cal. Time: 0::01::19 Timesteps: 62 Iteration: 3 No. Cells: 62 Stage: Storage

Fig. 5 Calibration screen in FIDO showing solution for 3 parameters.