

WinSRFR 5.1

User Manual

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ABSTRACT

WinSRFR is a software package for the hydraulic analysis of surface irrigation systems. The software integrates four different components: 1) an unsteady flow simulation engine that can be used to predict the surface and subsurface flow of water for a known system geometry, infiltration and roughness conditions, and boundary conditions; 2) tools for evaluating the performance of irrigation systems and for estimating infiltration and roughness conditions from field-measured data; 3) tools for designing irrigation systems, and 4) tools for optimizing the operation of existing irrigation systems. The software was developed for both practical uses and research. WinSRFR Version V. 5.1 introduces: a) a new framework for defining furrow infiltration; b) a semi-physical option for modeling furrow infiltration; c) an option for simulating border/basin irrigation with infiltration given by the Richards equation; d) EVALUE, a new parameter estimation component; e) an option for simulating fertigation, and; f) additional options for specifying furrow infiltration in the Design and Operational Analysis Worlds.

In Memoriam

This work is dedicated to the memory of Dr. Theodor S. "Fedja" Strelkoff (1932-2018), a pioneer in the field of hydraulic modeling of surface irrigation systems, the developer of the SRFr simulation engine, a valuable mentor and colleague, and a friend.

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Part I

Basics

CHAPTER 1

WELCOME TO WINSRFR

WinSRFR is a software package for the hydraulic analysis of surface irrigation systems. Intended users are irrigation specialists, consultants, extension agents, researchers, university level instructors and students, and farmers with a moderate understanding of irrigation principles and hydraulics. The software offers four analytical functionalities, which are identified in this document as WinSRFR Worlds. These functionalities are:

- | | |
|-----------------------------|---|
| Simulation: | Tools for predicting the surface and subsurface flow of water |
| Event Analysis: | Tools for evaluating the performance of irrigation events from field measurements and tools for evaluating infiltration and hydraulic resistance parameters |
| Physical Design: | Tools for optimizing the physical layout of a field |
| Operations Analysis: | Tools for optimizing the inflow rate and irrigation time |

These functionalities are accessible through the four color-coded World buttons (Figure 1.1). Pressing one of these buttons will launch the corresponding World Window, shown in the same figure.

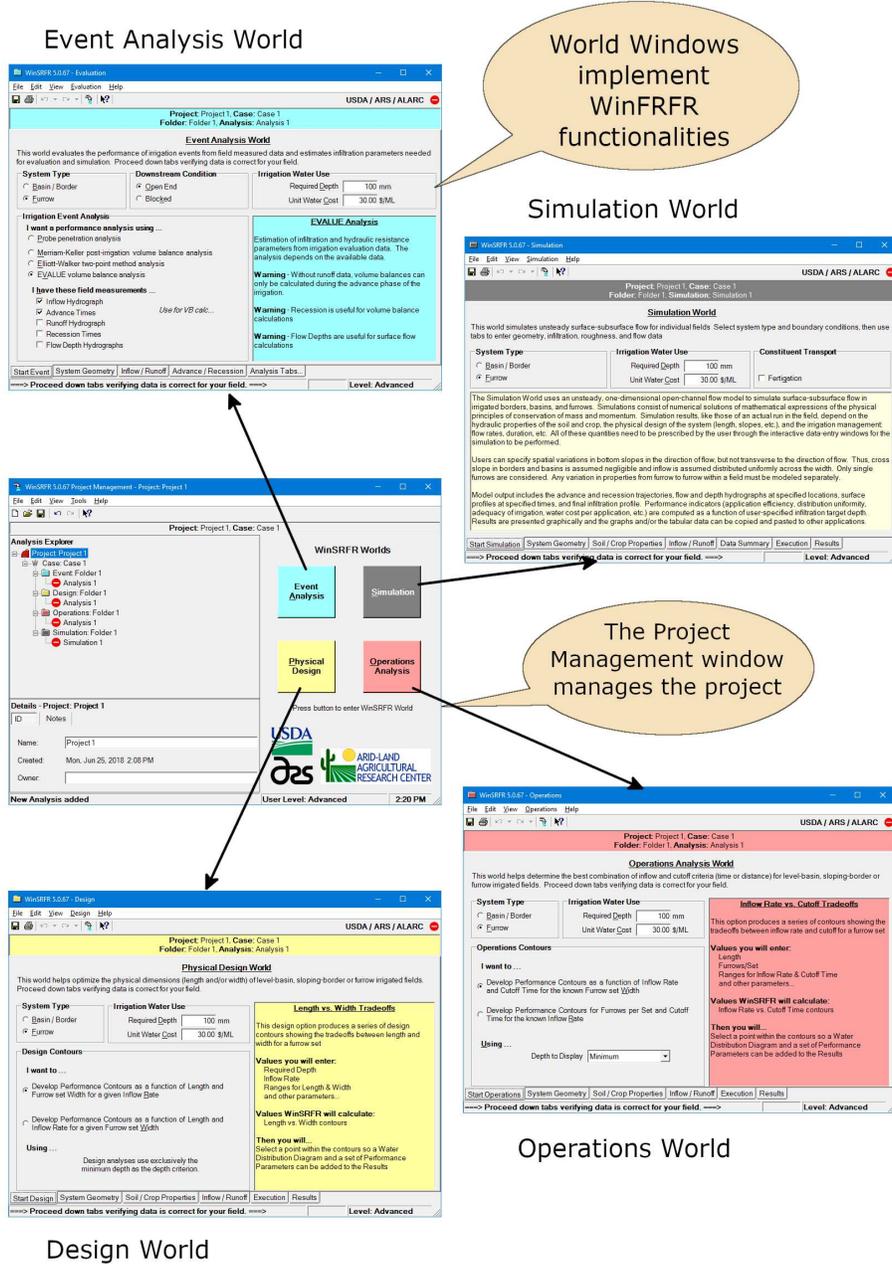


Figure 1.1: WinSRFR's Four Worlds of Functionality

1.1 Quick Start

Users familiar with the use of Windows applications, with surface irrigation engineering concepts, and with the use of simulation models, can jump directly to Chapters 5 and 6 and refer to Chapters 1-4 as needed. In particular, readers should concentrate on the following sections:

- Chapter 2
 - 2.1
- Chapter 5
 - 5.1
 - 5.2, 5.2.1, 5.2.2
 - 5.3, 5.3.1
 - 5.4, 5.4.1, 5.4.1.1, 5.4.2, 5.4.2.1, 5.4.2.2
 - 5.5, 5.5.1, 5.5.3
- Chapter 6
 - 6.1
 - 6.2, but exclude 6.2.2

1.2 Release History

<u>Version</u>	<u>Year</u>	<u>Key Features</u>
1.1	2006	Integrated the functionality of the DOS programs SRFR, BASIN, and BORDER into a single Windows application. WinSRFR 1.2, released May 2007, addressed several issues and bugs in the first release.
2.1	2007	Provided Merriam-Keller analysis support for all infiltration functions and all field cross sections, support for design and operations of furrow irrigated fields. contour functionality across all field cross sections and integration of the latest SRFR simulation engine

3.1	2009	Replaced the Physical Design and Operations Analysis procedures based on static databases of pre-computed unsteady flow solutions with volume balance solutions tuned with zero-inertia simulation results. The new procedures expanded the range of options used to specify infiltration characteristics for physical design and operational analysis problems. They also expanded the physical design and operational analysis functionality to include close-ended borders and furrows, level furrows, and furrows with cutback
4.1	2012	Reprogrammed the simulation engine SRFR using an object-oriented architecture, to facilitate code maintenance and continued development. SRFR communicates with WinSRFR via an application programming interface (API). Added batch-job capabilities to the Simulation World. Added the option of modeling infiltration in borders/basins with the Green-Ampt equation (Simulation World only).

1.3 What is New in Version 5.1

- Infiltration options
 - Revised framework for defining furrows infiltration options (all Worlds)
 - Option for modeling –depth dependent infiltration in furrows using the model of Warrick et al. (2007), in combination with the Green-Ampt equation (Simulation and Event Analysis only).
 - Option for running border and basin simulations coupled to the Richards equation using the HYDRUS-1D model (Simulation only)
- EVALUE, a parameter estimation component adaptable to various data configurations and infiltration models
- Fertigation option: simulation of non-reactive solute transport based.
- Design and Operational analysis for furrows using the NRCS and representative upstream wetted perimeter infiltration options.

1.4 Installation

1.4.1 Operating system and hardware requirements

WinSRFR was developed using Microsoft's .NET Framework 4.5 for the Windows operating system. To ensure proper installation and operation, the application must be installed on a

personal computer configured as follows:

Supported Operating Systems WinSRFR 5.1 is fully supported under Windows 10. It is not guaranteed to work with previous versions of the Windows OS.

Additional Software Requirements

Microsoft's .NET Framework 4.5 (Installed by the WinSRFR Installer if necessary)

Storage Requirements

- 20 MB for the program. Project files can each be several MB in size.
- 30 MB for the initial installed project files.

Monitor

A monitor with 1024 x 768 pixels or better resolution is recommended but the application can work with lower resolutions. Use the View/Size menu command to select a resolution compatible with your display.

1.4.2 Installation / uninstallation procedures

- The installation program AlarcWinSfr51Setup.exe will decompress all needed files, register libraries with the Windows operating system, and create needed directories. The program must be uninstalled using the Add/Remove Programs command under the Windows Control Panel. This is needed in order to correctly unregister the application and all its associated files.
- By default, the program will install under the C:\Program Files (x86) folder and create a \USDA \WinSRFR 5.1 subdirectory. Other USDA-ARS developed software may also install under the folders \USDA.
- Example project files will install under the C:\ProgramData folder and create a \USDA \WinSRFR subdirectory. It is recommended to keep a clean copy of these files in the installation directory, and to create working copies of them in a user-selected directory. To easily access these files, use the Windows File Manager to navigate to C:\ProgramData\USDA\WinSRFR\X.X\Examples. Be aware that X.X is the software release number (e.g., 5.1).

1.4.3 Settings for international (non U.S.) installations

WinSRFR was developed using a U.S. Windows installation. Windows allows the user to adapt the display of numbers and dates using the Control Panel/Regional and Language Options /Regional Options Tab. The Regional Settings for some non-U.S. locations can cause WinSRFR to misinterpret numbers entered through the user interface. At this time, the only way to avoid this problem is by displaying numbers using the U.S. settings (use period as the decimal symbol, comma as the digit grouping symbol, and minus as the negative sign symbol). The numerical display can be customized using the Customize button in the Windows Regional Options Tab.

1.4.4 Accessibility issues

WinSRFR is designed to meet the accessibility guidelines set forth in the Certified for Windows logo handbook:

- Support standard system size, color, font, and input settings. This provides a consistent user interface (UI) across all applications on the user's system.
- Ensure compatibility with the High Contrast option for users desiring a high degree of legibility (see Windows Settings/High Contrast).
- Provide documented keyboard access to all features. This allows the user to interact with the application without requiring a pointing device, such as a mouse. See Keyboard Navigation.
- Provide notification of the keyboard focus location. It should always be apparent both to the user and programmatically which application window has the focus. This requirement also enables the use of the Magnifier and Narrator accessibility aids.
- Convey no information by sound alone. Applications that convey information by sound must provide other options to express this information.

WinSRFR has been tested with these Microsoft supplied accessibility aids:

- Magnifier - Magnifies a portion of the computer's desktop for easier viewing
- Narrator - Reads the names, values and actions associated with displays and controls

1.5 Compatibility

WinSRFR 5.1 is backward compatible with files created with previous versions of the software (1.1, 2.1, 3.1, 4.1). Project files created or saved with WinSRFR 5.1 are not compatible with earlier versions. Thus, if a project file created with 4.1 is opened and saved with 5.1, that project may no longer be accessible with 4.1.

1.6 Disclaimer

The software can be used to analyze both practical and theoretical irrigation problems. The mathematical representations of irrigation systems is based on a combination of physical principles and empirical relationships. The computational procedures have been tested using a large number of scenarios but are not guaranteed to be error free. Furthermore, results need to be interpreted judiciously because they depend on uncertain inputs and assumptions that may be violated in the field. The United States Department of Agriculture and the Agricultural Research Service accept no liability or responsibility of any kind resulting from installation and use of this software.

1.7 Credits and Acknowledgments

WinSRFR was developed and is supported by:

USDA	United States Department of Agriculture
ARS	Agricultural Research Service
ALARC	Arid-Land Agricultural Research Center

Mr. J.L. Schlegel was the lead software developer for WinSRFR. The unsteady flow simulation engine was developed by Dr. T.S. Strelkoff. Basin design and operational procedures were developed by Dr. A.J. Clemmens, Dr. A.R. Dedrick, and Mr. R.J. Strand. Border design and operational procedures were developed by Dr. T.S. Strelkoff, Dr. A.J. Clemmens, Dr. M. Shatanawi, Mr. B.V. Schmidt, and Mr. E. J. Slosky. Furrow design and operational procedures were developed by Dr. A.J. Clemmens. Procedures for event analysis were developed by Dr. E. Bautista and Dr. A.J. Clemmens.

This software package was developed with input and feedback from the USDA-Natural Resources Conservation Service (NRCS). In particular, the contributions of Mr. Clarence Prestwich and Peter Robinson, West National Technology Support Center, USDA-NRCS, are acknowledged.

Dr. Guido Wyseure, Professor, Faculty of Bioscience Engineering; Katholieke Universiteit Leuven, Belgium, Dr. Richard Cuenca, Professor Emeritus, Biological and Ecological Engineering, Oregon State University, USA, and Mr. Clarence Prestwich, Irrigation/Drainage Engineer, USDA-NRCS, conducted technical reviews for the software and manual for version 5.1. We are indebted to them.

Last, we thank users who have provided us with questions, comments, criticisms, and suggestions throughout the years. We encourage other users to do the same.

1.8 Contact Information

Comments, questions, and bug reports can be directed to:

winsrfr@usda.gov

1.9 Manual Conventions

The manual uses text formatting to highlight controls, forms, menu commands, and keyboard combinations that need to be used to carry out a particular task. The formatting convention is summarized below:

Input control (text box, option button, drop-down list, drop-down list item)	Example
Tab Page, window	Example
Menu item	Example
Keyboard sequence	Example

The electronic version of this manual makes extensive use of hyperlinks. Use those hyperlinks to navigate to referenced items (equations, figures, tables, chapters, sections, citations). Use then the Adobe Acrobat Reader® *Page Navigation/Previous View* menu command (**Alt-Left Arrow**) to return to the original cursor location. When hovering with the mouse over hyperlinked text, the cursor will change from the conventional vertical bar to a hand pointer. For example, use the hyperlink at the end of this sentence to navigate to Table 4.4.

1.10 Notation

1.10.1 Flow variables

A_y	Cross-sectional flow area
A_z	Infiltration area (Infiltration volume per unit length)
BW	Bottom width of a trapezoidal furrow cross section
C	Constant of the power law relationship for a parabolic furrow
C_o	Solute concentration
FS	Furrow spacing
H	Water surface elevation
K_x	Longitudinal solute dispersion coefficient
L	Field length
M	Exponent of the power law relationship for a parabolic furrow
n	Manning n
p	Empirical power advance law constant
q_{in}	Unit inflow rate (Flow rate per unit width or per furrow)
Q	Flow rate
Q_{in}	Inflow rate (Flow rate at $x = 0$)
Q_s	Solute inflow rate
r	Empirical power advance law exponent
R	Hydraulic radius
S_0	Field bottom slope
S_f	Friction slope
SS	Side slope of a trapezoidal furrow cross section
T	Time
T_a	Advance time

T_{co}	Cutoff time
T_L	Advance time to end of the field
T_R	Recession time
TW	Top width of flow
V_{in}	Inflow volume
V_{ro}	Runoff volume
V_y	Surface volume
V_z	Infiltration volume
V_z^*	Predicted infiltration volume
W	Border/basin/furrow set width
W_{100}	Flow width at 100 mm (4 in)
WP	Wetted perimeter
X	Distance
X_A	Advance distance
XR	Cutoff ratio (simulation output): if $T_{co} < T_L$, $XR = X_A/L$ else $XR = T_{co} / T_L$.
Y	Flow depth
Y_{max}	Maximum flow depth
z	Infiltration depth (Infiltration volume per unit area)
τ	Opportunity time
σ_y	Surface shape factor
σ_{z1}	Subsurface shape factor
σ_{z2}	Subsurface shape factor

1.10.2 Infiltration and roughness parameters

a	Empirical infiltration exponent
b	Empirical steady-state infiltration rate.
c	Empirical instantaneous infiltration depth, attributable to soil macropores and cracks
h_f	Green-Ampt wetting front pressure head
k	Empirical infiltration constant
K_s	Hydraulic conductivity
n	Manning roughness coefficient
z_c	Characteristic infiltration depth
γ	Empirical fitting parameter of the Warrick-Green-Ampt equation
θ_0	Initial volumetric water content
θ_s	Saturated volumetric water content
τ	Infiltration opportunity time

τ_b	Branch Time - for infiltration given by the Branch function, the time at which infiltration rate becomes constant
τ_c	Characteristic infiltration opportunity time
τ_{req}	Opportunity time for required infiltration depth
τ_{100}	Characteristic opportunity time for 100 mm infiltrated depth
χ	Sayre-Albertson roughness coefficient

1.10.3 Performance measures

$ADlq$	Low-Quarter Adequacy ($ADlq = Dlq / Dreq$)
$ADmin$	Minimum Adequacy ($ADmin = Dmin / Dreq$)
AE	Application Efficiency ($AE = Dz / Dapp$)
$D(x)$	Function describing the final infiltrated depth as a function of distance along the field
$Dapp$	Average depth of applied water (applied volume/area)
Ddp	Average depth of deep percolation (deep percolation volume/area)
$Dinf$	Average depth of infiltrated water (infiltrated volume/area)
Dlq	Low quarter average infiltrated depth - average infiltration depth for the lower 25% percentile of the infiltration distribution.
$Dmin$	Minimum infiltrated depth
DP	Deep Percolation percentage ($DP = Ddp / Dapp \times 100$)
$Dreq$	Required infiltration depth
Dro	Average depth of runoff, or, runoff volume expressed as an equivalent average depth.
$DUlq$	Low-quarter distribution uniformity ($DUlq = Dlq / Dinf$)
$DUmin$	Minimum distribution uniformity ($DUmin = Dmin / Dinf$)
Drz	Root zone infiltration, i.e., infiltrated depth contributing to the irrigation target
$PAElq$	Potential application efficiency of the low quarter(attainable AE when inflow rate and cutoff time are such that $Dlq = Dreq$; see definition for AE)
$PAEmin$	Potential application efficiency of the minimum (attainable AE when inflow rate and cutoff time are such that $Dmin = Dreq$; see definition for AE)
RE	Requirement efficiency ($RE = Drz / Dreq \times 100$)
RO	Runoff percentage ($RO = Dro / Dapp \times 100$)
$Verr$	Volume balance error

1.10.4 Solute transport

C_e	Coefficient of the Elder equation
C_o	Solute concentration (mass/volume)
K_x	Longitudinal dispersion coefficient(area/time)
M	Solute mass

CHAPTER 2

WINSRFR FUNCTIONALITY

Engineering studies of surface irrigation systems begin with an evaluation of current performance based on field-measured data. The analysis determines the fate of the irrigation water: how much water was applied, how much infiltrated, the distribution of infiltrated water along the field, how much water contributed to satisfy the irrigation requirement, and how much was lost by deep percolation and runoff.

If performance is judged to be inadequate, the operation of the system needs to be examined. Such an analysis compares the performance tradeoffs of different combinations of inflow rate and cutoff time for the assumed average field conditions (infiltration, roughness, and target application depth). The analysis may identify a range of recommended inflow rates and cutoff times, or alternatively, may demonstrate that performance cannot be improved without improving the physical design.

An analysis of alternative system layouts may consider changes to the dimensions of the field (length and width) with the available flow rate, and/or to the bottom slope (if soil conditions allow). Similar to operations analysis, design analysis must compare the performance trade-offs of different combinations of design variables and must be conducted based on representative field conditions.

Field conditions, such as infiltration, hydraulic resistance, the available inflow rate, and even the bottom slope can be expected to vary over a field, and temporally during the irrigation season and over the course of multiple seasons. Hence, sensitivity tests are integral to hydraulic analyses of surface irrigation systems, to assess the degradation in performance with potential variations in field conditions. The ultimate objective is to identify robust operational and/or design recommendations, i.e., recommendations that will produce ac-

ceptable levels of irrigation performance under the expected range of field conditions.

WinSRFR functionalities were developed to support this analytical process. These functionalities, referred to as Worlds in the software, are Event Analysis, Operation Analysis, Physical Design, and Simulation. The following paragraphs provide an overview of these functionalities. Since the Simulation World is pivotal to the application, it is discussed first.

2.1 Hydraulic Simulation

The Simulation World is used to predict the surface flow and infiltration as a function of distance and time. Required inputs are the field geometry, the infiltration and hydraulic resistance functions, and the upstream (inflow hydrograph) and downstream (open or closed) boundary conditions. The infiltration and resistance functions are defined by the user-selected modeling approach and parameters representative of the field conditions.

Simulations are conducted with the simulation engine, identified in this document as SRFR (Bautista et al., 2016a; Strelkoff, 1990). SRFR solves the one-dimensional unsteady open-channel flow equations coupled with empirical/semi-empirical equations describing infiltration and channel roughness (see Appendix A). The surface flow equations represent the physical principles of conservation of mass and momentum. Given the relatively low velocities and Froude numbers that characterize surface-irrigation flows, the simulation engine solves simplified forms of the momentum equation. The zero-inertia (force equilibrium) model assumes that the pressure gradient, friction, and gravity are the only forces acting on the flow. This form of the equations can be applied to all practical field conditions and produce results similar to those computed with the full unsteady flow equations. The kinematic-wave model ignores the pressure gradient force and assumes that frictional forces are in balance with gravity, i.e., that flow is at normal depth everywhere. Such an assumption is reasonable with relatively large slopes and where the flow is not subject to backwater effects. The latter condition limits the application of the kinematic wave model to free-draining systems. Computations are faster and more robust with the simplified governing equations.

The SRFR engine can be configured to model basins, borders, and furrows, all under the assumption of one-dimensional flow. This means that all flow characteristics vary only with distance along the field length and time, i.e., not across the width. This also means that water does not flow between neighboring irrigation units. For borders and basins, the model is applicable to fields where the side-fall is negligible in comparison with the applied depth, infiltration and roughness are relatively uniform across the field width, and inflow is distributed uniformly along the upstream boundary. When water flows into a border/basin from a source point, this last requirement is clearly not satisfied. Nevertheless, the analysis is still applicable if the water spreads laterally over a relatively short distance.

Outputs include the advance and recession curves, the final infiltration profile, flow and depth hydrographs at specified locations, water surface profiles at specified times, and indi-

cators of hydraulic performance such as application efficiency, distribution uniformity, and adequacy of the irrigation. These outputs are summarized in graphs and tables.

The Simulation World also supports computations conducted by the other three Worlds. The simulation engine is used in the Event Analysis World to verify infiltration parameter estimates (computed with the post-irrigation volume balance and two-point method estimation procedures). In Operations and Design, the simulation engine is used to calibrate the volume balance computations and to verify the accuracy of the selected solution point.

SRFR can be run independently of WinSRFR, through its application programming interface (API) (Bautista et al., 2016a). SRFR classes and their functionality are available to the programmer through the API. The API is described in the document SRFR 5.0-API.docx and is available from the authors upon request.

2.1.1 Solute transport

Fertigation is the practice of distributing fertilizer with the irrigation stream. This practice can be analyzed with the Fertigation simulation option. This modeling tool couples the advection-dispersion equation to the equations of water flow. The advection-dispersion calculations are carried out after solving the water flow equations, assuming the following: a) the solute is injected at the field inlet at a known rate Q_s [L^3/T] and concentration C_0 [M/L^3], mixes perfectly with the water at that point, and is not present in the soil surface prior to the irrigation; b) the solute flow has no effect on the water flow, and; c) the solute travels without losses (other than infiltration) or transformations (i.e, is non- reactive). The simulation predicts the flow of solute in the stream and into the soil as a function of distance and time and, ultimately, its final mass density distribution along the field [M/L]. The model currently does not calculate the vertical distribution within the soil profile, and instead assumes a uniform distribution with depth at any location. In the case of furrow irrigation, the solute is also assumed to be distributed uniformly across the furrow spacing. If a fertigation simulation is conducted with infiltration computed with the one-dimensional Richards equation, using the HYDRUS-1D (Šimůnek et al., 2013) model, the solute distribution in the soil profile can be examined from the HYDRUS output files.

2.2 Event Analysis

The Event Analysis World is used to evaluate the hydraulic performance of irrigation systems from field data and to estimate field parameters (infiltration and hydraulic resistance). Those parameters are needed to conduct simulation, physical design, and operational studies. Previous releases of WinSRFR provided 3 analytical options: 1) Probe penetration analysis (USDA-NRCS, 1997); 2) the Merriam-Keller post-irrigation volume balance analysis (Merriam and Keller, 1978), and 3) the Elliott-Walker Two-Point analysis (Elliott and Walker, 1982). WinSRFR 5.1 adds a fourth option, referred to as EVALUE (Bautista and Schlegel, 2017a; Strelkoff et al., 1999). Probe penetration analysis is used exclusively for evaluation

of performance. The other three procedures have parameter estimation capabilities.

The post-irrigation volume balance, two-point, and EVALUE methods use volume balance analysis for the estimation of infiltration parameters. Appendix B.1 explains the principles of volume balance analysis. The estimation procedures offered by WinSRFR vary in complexity and data requirements. Procedures that use more data and, particularly, measurements from different phases of an irrigation event have the potential for producing more accurate parameter estimates than procedures that use limited data. However, all estimates are, ultimately, uncertain, because of the spatial and temporal variability of the infiltration and hydraulic resistance processes. Parameter estimation is most useful when practiced repeatedly in space and time, and thus when used to characterize the range of infiltration and roughness conditions for a field.

As with infiltration, models of hydraulic resistance need to be calibrated for the particular field conditions. An important limitation of procedures for the estimation of infiltration parameters, in particular methods based on volume balance, is that they assume that hydraulic resistance is known. Since different infiltration solutions can be computed depending on the assumed roughness coefficient, hydraulic resistance needs to be characterized independently from infiltration. This can be done with the EVALUE option, using flow depth measurements. It is also possible to obtain reasonable roughness estimates with the Merriam-Keller method, as implemented in WinSRFR, but only under a limited range of hydraulic conditions.

2.2.1 Infiltration profile analysis from probe penetration data

Probe penetration analysis is an evaluation technique that relies on measurements of the post-irrigation depth of the infiltration wetting front. This depth is determined by driving a metal probe through the wetted profile at several locations along the field. It is mainly applicable in heavy to medium-textured soils. The water penetration depth is used to estimate the post-irrigation depth of infiltration water contributing to the irrigation requirement, D_{req} (also referred to in this manual as the irrigation target). D_{req} is calculated considering the depth of water needed to replace the root zone soil water deficit and leaching requirements. The analysis requires measurements of inflow and outflow, a description of the root zone's available water capacity, and pre-irrigation soil water deficit. The applied and outflow volumes (for open-ended systems) are used to calculate a post-irrigation mass balance. Outputs of the analysis are: a) the applied, runoff, and infiltrated depth totals; b) infiltration depth profile; and; c) performance measures, including application efficiency and uniformity.

2.2.2 Merriam-Keller post-irrigation volume balance

The Merriam-Keller procedure (Merriam and Keller, 1978) is an infiltration parameter estimation method that uses a single volume balance relationship, calculated at the end of the irrigation (at the final recession time), when V_y in Eq. (B.1) is equal to zero. It is

also referred to as the post-irrigation volume balance (PIVB) method. It was originally developed to solve for the constant k of the Kostiaikov equation with the exponent a given. Required inputs are the final inflow volume, final runoff volume (for free-draining systems), and advance and final recession times at selected distances along the field. A_z is calculated at discrete locations from the opportunity times determined from the advance and recession data (Bautista et al., 2009a) and those values are then used to calculate Eq. (B.3) using trapezoidal rule integration. Because the method uses a single volume balance equation, it can solve for only one parameter (or for an infiltration family, which are fixed relationships). Other parameters, which typically are also unknown, need to be provided as inputs.

The Merriam-Keller procedure was developed prior to the development of simulation models. As originally conceived, it is not a very reliable estimation method because it tries to infer a non-linear function from a single measured point on that curve, as illustrated in Figure 2.1. The solid curve represents the infiltration function for a hypothetical field and the dot the infiltration volume (per unit area) for the average intake opportunity time of the observed irrigation event. Many functions, defined by different parameter combinations, can pass through that point. Two of them are shown as dashed curves.

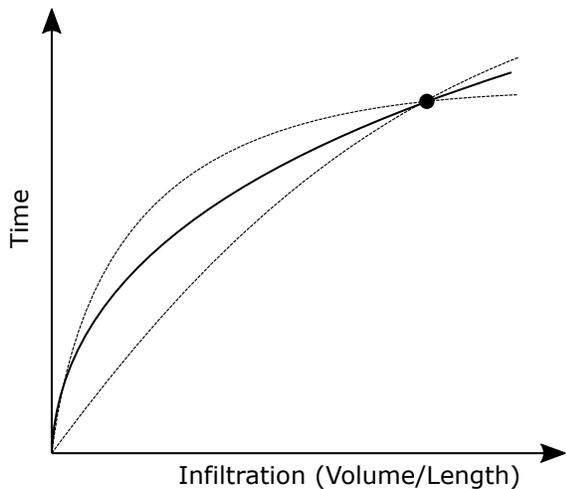


Figure 2.1: Estimation of an infiltration function with the Merriam-Keller method

WinSRFR combines the Merriam-Keller method with hydraulic simulation, to improve the reliability of the infiltration parameter estimates. Infiltration can be represented with most empirical equations offered by WinSRFR. Parameters are adjusted iteratively with the help of simulation to better match the available measurements. Those measurements provide, implicitly, additional points along the curve of Figure 2.1.

Alternatively, the reliability of the estimated parameters can be improved by measuring more points on the infiltration curve, i.e., by using volume balance calculations at other times. This can be done with the EVALUE method, described later.

2.2.3 Elliot and Walker's two-point method

The Elliott and Walker (1982) two-point method is a parameter estimation method that uses two volume balance equations, both calculated during the advance phase of the irrigation. The method solves for the parameters K [L^2/T^a] and a [\cdot] of the Extended Kostiaikov equation (see Section 5.4) and, with B (the steady infiltration rate) calculated from steady-state inflow minus outflow measurements. No other infiltration equations can be used in

combination with this method. Required inputs are the advance time-distance pairs, the inflow volume, and the steady infiltration rate. The method was developed primarily for use with sloping, free-draining furrow irrigation systems. Although this method adds a second measurement to the estimation problem depicted in Figure 2.1, both measurements are restricted to the advance phase of the irrigation. There are other limitations to this method, one of which is that with only two measurements, it is difficult to say if those measurements are representative or if they are affected by field non-uniformities (Bautista et al., 2009b).

WinSRFR 5.1 modifies the original method of Elliott and Walker (1982). The modifications are discussed in Appendix B.2.

2.2.4 EVALUE method

EVALUE (Bautista and Schlegel, 2017a) is a volume-balance based procedure, supported by unsteady flow simulation, for the estimation of infiltration and hydraulic resistance parameters. The method can be applied to different data configurations and different infiltration and hydraulic resistance models. Since the post-irrigation volume balance and two-point method described in the previous sections are particular instances of the more general EVALUE method, scenarios originally created for those methodologies can be analyzed with EVALUE.

The volume balance analysis is formulated by the software from data provided by the user. An analysis can be conducted using only advance times to specified distances. Additional measurements that can be provided are recession times, runoff rate (in the case of free-draining systems), and flow depths as a function of time and distance. A premise in the development of EVALUE is that it will produce more reliable results when volume balance is calculated a multiple times, and when the data set includes information from both the advance and post-advance phases of the irrigation event. This reduces the sensitivity of the solution to anomalous measurements. Flow depths are particularly useful and, furthermore, are required to characterize hydraulic resistance independently from infiltration. Those variables will become easier and less costly to measure with the development of micro-electronic sensors. At the same time, EVALUE was designed to handle a wide range of input data configurations, recognizing that some users may prefer to collect as few measurements as possible, or that omissions, equipment failures, and other practical difficulties may prevent an evaluator from obtaining all the desired data.

As with other volume-balance-based parameter estimation methods, EVALUE is used to estimate the parameters of empirical infiltration equations. Such an analysis assumes that infiltration depends on opportunity time only. In addition, EVALUE can be used to estimate the parameters of flow-depth dependent infiltration equations (see Section 5.4). This includes the semi-physical models Green-Ampt and Warrick-Green-Ampt equations, and also the empirical Modified Kostiaikov equation when used in combination with the Local Wetted Perimeter option (furrows).

An EVALUE analysis can use either hydraulically estimated surface volumes or volumes derived from measured depths. Which method is used depends on the available data. When

the former approach is used, the surface shape factors have to be refined with the help of hydraulic simulation. The available data also determines how the integral B.3 is computed. Whenever possible, numerical integration is used but when advance is measured only at a few locations, the preferred approach is a power law integral similar to Eq. B.4. As with the two-point analysis, the subsurface shape factors need to be refined with the help of hydraulic simulation.

If flow depth measurements are provided, they can also be used to estimate the coefficient of hydraulic resistance. The analysis involves comparing simulated depths with measured values and can be conducted using either the Manning or Sayre-Albertson equations.

2.3 Operational Analysis

The Operations Analysis World examines irrigation performance as a function of inflow rate and cutoff time. Required inputs are the geometric configuration of the system, infiltration, hydraulic roughness, and the irrigation requirement (target application depth). The outputs consist of performance contours. These are analogous to the constant-elevation curves on topographical maps, which illustrate peaks and valleys in the landscape; performance contours illustrate the peaks and valleys in performance as a function of the operational variables. With these contours, the user can:

- Examine how the operational variables affect application efficiency, distribution uniformity, deep percolation, and runoff losses.
- Identify solutions (combinations of inflow rate and cutoff time) that satisfy the irrigation requirement (D_{req}). Two different criteria can be applied:
 - The minimum infiltration depth value in the final infiltration profile matches the irrigation target ($D_{min} = D_{req}$)
 - The low-quarter infiltration depth (the average depth for the quarter of the field receiving the least infiltration) matches the irrigation target ($D_{lq} = D_{req}$)
- Examine the performance trade-offs for solutions that satisfy the requirement. The contours can be used to identify solution regions that are likely to be very sensitive to slight differences between the actual field conditions and those assumed in the analysis, including solutions that may lead to incomplete advance.

Specific combinations of operational variables in the performance contours can be examined with the Water Distribution Diagram. This tool dynamically updates the displayed final infiltrated profile and hydraulic performance values as the user navigates the contours.

Operations Analysis procedures are applicable to furrow and border/basin irrigation systems, with either an open or closed downstream end. Different options are available for specifying infiltration and hydraulic roughness conditions, but the analysis assumes that those properties are uniform along the field. Likewise, the analysis assumes a uniform cross

section and bottom slope. The analysis can assume a constant inflow rate or a cutback configuration.

The performance contours are generated from simulation results computed at selected grid points in the user-defined contouring region (a range of discharges and cutoff times). Contour lines are developed by interpolation from those points. To reduce the computational effort, which can be substantial even with a coarse grid, WinSRFR develops the discrete simulation solutions using volume balance calculations calibrated with unsteady simulation results. Calibration is performed at a selected grid point within the contouring region. Volume balance solutions most closely match the unsteady simulation results when near the calibration point. The software allows the user to contrast the volume balance and unsteady simulation performance predictions at any selected solution point.

Modified Feature!

In previous versions of WinSRFR, operational analyses of furrow systems were restricted to a single infiltration wetted perimeter option, furrow spacing (see Section 5.4.2.1). Version 5.1 expands those choices to include the NRCS and Representative Upstream Wetted Perimeter options.

2.4 Physical Design

The Physical Design World is used to find field layouts (length and width for a known available inflow rate, or length and unit inflow rate for a given width) that produce acceptable levels of performance. Required inputs are the target application depth, field slope, soil and crop characteristics, and available inflow. Outputs consist of a set of performance contours, similar to those computed with Operations Analysis. In contrast with the Operations Analysis World, all solutions displayed in the Physical Design contours match the minimum infiltration value to the target depth. The design is based on the concept of Potential Application Efficiency of the Minimum (*PAE_{min}*), which is defined as the application efficiency when the minimum infiltration depth (the point along the field receiving the least amount of water) matches the irrigation requirement. With these contours, the user can:

- Examine how the design variables affect individual performance indicators the potential application efficiency, distribution uniformity, deep percolation, runoff losses, etc.
- Identify ranges of solutions that will deliver acceptable levels of performance.
- Examine the performance tradeoffs between different solutions, i.e, examine the sensitivity of solutions to slight differences between the actual field conditions and those assumed in the analysis.

Procedures in the Physical Design World apply to furrow and border/basin systems with an open or closed downstream end. Various options are available for specifying infiltration and hydraulic roughness conditions. The analysis assumes either a constant inflow rate or

a time-based inflow cutback. The analysis also assumes a constant slope and cross-section along the field. Design analyses often involve examining alterations to the field slope. For those types of comparisons, the user needs to create design scenarios with different slope values.

The solution region (e.g., the range of lengths and widths) to be explored is user-specified. The software computes design solutions at grid points of the solution region, using the same procedures as in Operations Analysis (volume-balance calculations calibrated by unsteady simulation results). Contour lines are then developed by interpolation. As with Operations Analysis, Physical Design of furrow irrigation systems can now be conducted using the NRCS and Representative Upstream Wetted Perimeter options, in addition to Furrow Spacing.

CHAPTER 3

CREATING AND MANAGING PROJECTS AND SCENARIOS

In WinSRFR, a scenario is the fundamental data structure needed to conduct Event, Operations, Design, and Simulation analyses. The scenario contains all the data needed for particular type of analysis. A WinSRFR project file is a collection of related scenarios, representing different combinations of input variables and/or computational options.

Projects and their corresponding scenarios are created and managed through the main user interface component, the Project Management Window. Individual scenarios within a project are edited and executed through the World Windows. World Windows are also used to view and extract outputs. World Windows are specific to each type of analysis and, thus, differ in their required inputs and resulting outputs.

3.1 Project Management Window

The Project Management Window (Figure 3.1) (i.e., the Project Manager) is the first form displayed by the application. It consists of three graphical controls:

- The **Analysis Explorer**
- The **Analysis Details**
- The **WinSRFR World Buttons**

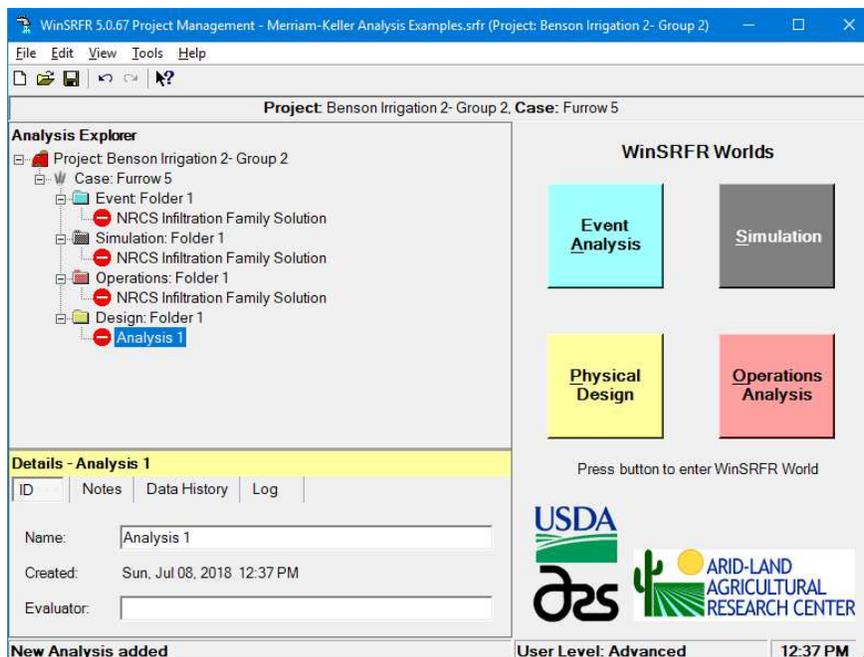


Figure 3.1: The Project Management Window

3.1.1 Analysis Explorer

The **Analysis Explorer** (Figure 3.2) is the control that manages WinSRFR projects. Like the Windows Explorer the Analysis Explorer displays a hierarchical tree-view of data objects in a project. Items in the hierarchy are selected by single-clicking on them. Double-clicking opens the item. An open-folder can be closed (collapsed) by double-clicking. Only one project can be loaded into WinSRFR at a time.

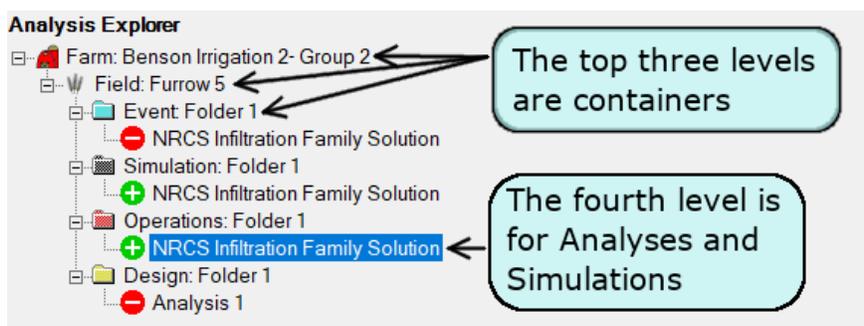


Figure 3.2: The Analysis Explorer

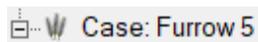
3.1.1.1 Analysis Explorer Folders

The top three levels in the Analysis Explorer are folders that help organize scenarios. Scenarios reside at the fourth (i.e. right-most) level.



The top-level container is the **Project Folder**; only one Project per file is allowed.

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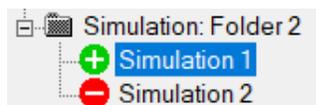


Below the Project folder are **Case Folders**. These folders help organize related data in a Project file. For example, information from different fields in a farm can be stored in separate Case folders.

A project file is likely to be associated with a farm, and a case with a field within a farm. Hence, WinSRFR use the concepts of Project and Farm folder interchangeably. Likewise, Field and Case Folders are synonymous terms. Use the *Edit/Nomenclature* command to select the preferred terminology.



The last level in the folder hierarchy is the **World Folder**. These folders are color-coded according to the types of scenarios that they can store, e.g., a Simulation Folder can only store Simulation scenarios. A Case (Field) Folder contains at least one World Folder, and can contain two or more World Folders of any type. World folders are initially empty.



Analytical scenarios reside at the fourth level. A scenario consists of inputs that describe the particular field, execution criteria, and the computed outputs.

3.1.1.2 Creating and saving projects

A project is created automatically when the application launches. New projects contain a single case folder and an empty folder for each World type. Projects are saved to a .sfr file using the *File/Save As* or *File/Save commands*. Saved projects are opened using the *File/Open* command, by selecting from a list or recently opened projects, or from the list of Example projects (provided with the installation file). The program can be also configured to open the most recently saved project (see Section 4.2). While only one project can be opened at a time, data from two different projects can be viewed simultaneously by running a second instance of WinSRFR. This procedure can be used also to copy data from one project to another.

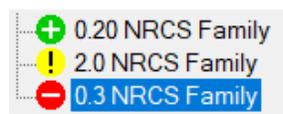
3.1.1.3 Creating, copying, moving, and deleting folders and scenarios

If a World folder is empty, its icon is labeled **Double-Click to Start Analysis**. Perform this action to create a scenario. More generally, folders and scenarios are created (*Start New*

Analysis), deleted (*Remove*), moved (*Cut/Paste*) or cloned (*Copy/Paste*) using context menus. A context menu is invoked by selecting the item to be edited and pressing the right mouse button. Context menus differ depending on the selected level within the Analysis Explorer hierarchy.

Folder and scenario objects can be pasted only to folders that can store like objects. Thus, a scenario can be pasted to a World Folder, but not to a Case Folder. Likewise, World Folders can only be pasted to Case (Field) folders, while Case folders can only be pasted to the upper level of the Explorer hierarchy (the project). WinSRFR enforces these restrictions by enabling or disabling the *Paste...* command in context menus.

3.1.1.4 Execution status of scenarios



Scenario icons are used to notify the execution status of the scenario. Initially, the icon is red and has a minus sign. This, means that the scenario has not been executed. The icon turns green with a plus sign after a successful execution, which indicates that the scenario contains viewable results. A yellow icon with an exclamation point indicates the execution failed, or that results are invalid. If the data of a successfully executed scenario is modified, the status icon will change back to red.

NOTE

The application occasionally fails to refresh the Analysis Explorer after executing a scenario or after clearing all results. Click on *View//Refresh* or F5 to update the Analysis Explorer.

3.1.2 Analysis Details

The **Analysis Details** pane displays two editable (**ID** and **NOTES**) data fields. These fields are accessed by clicking on their respective tabs (Figure 3.3). Previous versions of the software also displayed two non-editable fields (Data History and Log). Those fields were used to diagnose version incompatibilities and are no longer available.

ID: This field is an identifier for folders and scenario objects. New objects are initially named using a default naming scheme. The name is user-editable. Names in the folder must be unique. The software will issue an error message when entering an identifier already in use.

Notes: Enter a description of a project, folder, or scenario in this field. Notes are not required, but are recommended.

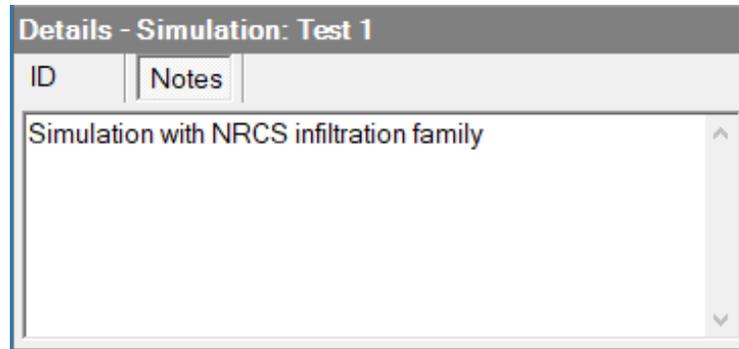


Figure 3.3: The Analysis Details pane

3.1.3 WinSRFR World Buttons

The WinSRFR **World Buttons** are short-cuts. The application creates an initial scenario in the corresponding World when one of these buttons is pressed. World Buttons and their corresponding **World Window** are identified using the color scheme shown in Figure 3.4.



Figure 3.4: World Buttons

3.2 World Windows

World Windows provide access to the analytical functionalities of WinSRFR. They share a common layout, which is explained next. Details of data inputs expected by these Windows

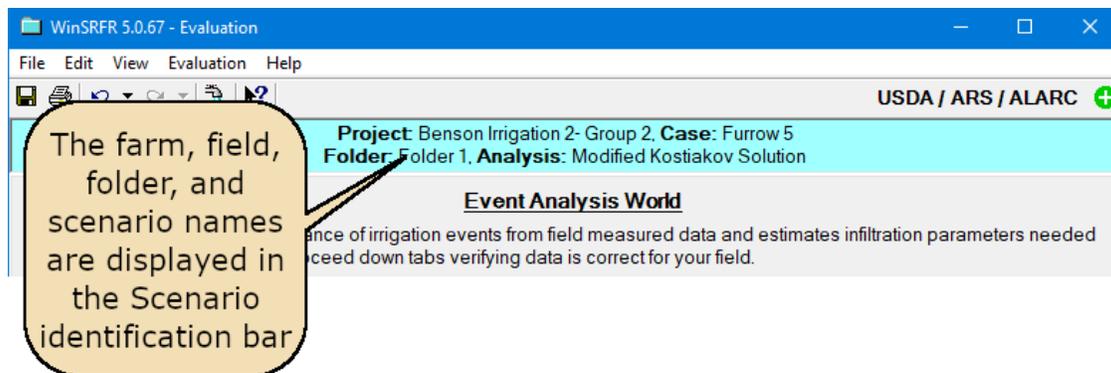


Figure 3.5: World Window: scenario identification

are explained in Chapter 5.

The title bar of each World Window (Figure 3.5) displays the software version and the World Name. Below the menu is the Scenario Identification bar, which is color coded to match the colors of the World buttons in the Project Manager. It displays the name of the currently loaded scenario and its path in the Analysis Explorer.

Data for each scenario are provided through a series of tabbed pages (Figure 3.6), which are accessible through the tab controls located at the bottom of World Windows. The left-most **Start** Tab page is used to select the irrigation system type (basin/ border, or furrow), and specify other preliminary information. Data options displayed in other tab pages depend on the user selected system type and preliminary options.

Data tab pages to the right of **Start** organize data inputs into logical groups: inputs that define the geometry of the system (**System Geometry**), inputs that define roughness and infiltration properties (**Soil/Crop Properties**), inputs that define water inflows and outflows (**Inflow/Runoff**), and inputs specific to an analysis type (in particular, inputs for each analytical option in the **Event Analysis World**).

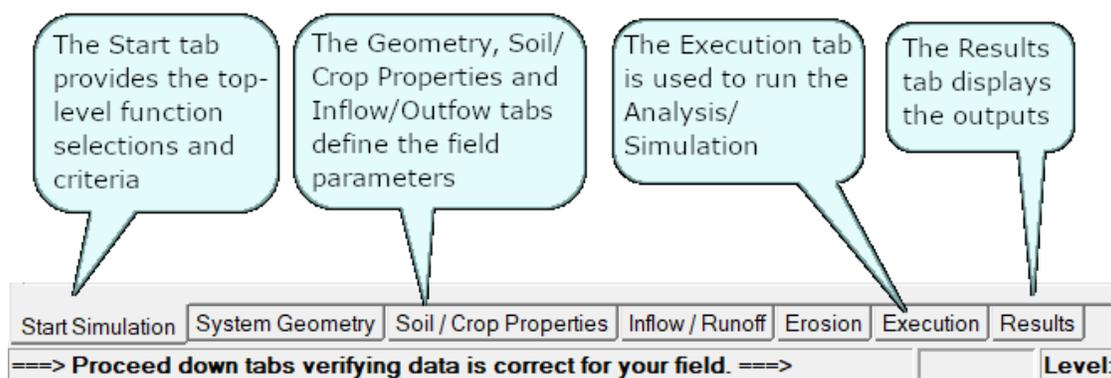


Figure 3.6: World Window: tab pages

With the Simulation, Operations, and Design Worlds, the Execution tab is the next-to-last tab page. Execution criteria can be set or edited from this page. If the execution is successful, results are displayed in **Results** tab pages. The tab controls for these pages are located near the top of the page (Fig. 3.7). Pressing any input tab control hides the Results tab pages. Pressing the Results tab control displays those pages again. Editing any input closes the Results tabbed pages, as the available results will no longer correspond to the specified data.

In the Event Analysis World, the last tab control is labeled **Analysis Tabs**. This tab hides the data input tabs and displays instead the analysis tab pages. When viewing the analysis tabs, press the first tab control, labeled **Data Tabs**, to return to the data input tab pages. Analysis tab pages differ depending on the selected analysis (Probe Penetration, Merriam-Keller, Two-Point or Evaluate). Each analysis tab page represents a component of the analysis. That tab page may provide information pertinent to the analysis or may request user input. For example, a component of Two-point analyses is the determination of surface volumes. These calculations are handled mostly by the software and are displayed in a tab page for informational purposes. Another component is the calculation of the infiltration parameters, which requires user actions. A separate tab page is provided for that purpose. The last two tabbed pages are Verify and Results. The former is used to test the estimated results with simulation; the latter displays field-measured versus simulated values in a series of tabbed pages, as with other Worlds. This grouping of tabbed pages for Event Analysis is new in WinSRFR 5.1. It was adopted to clearly separate the data input actions from the computations, and to reduce the number of tab controls displayed at any time.

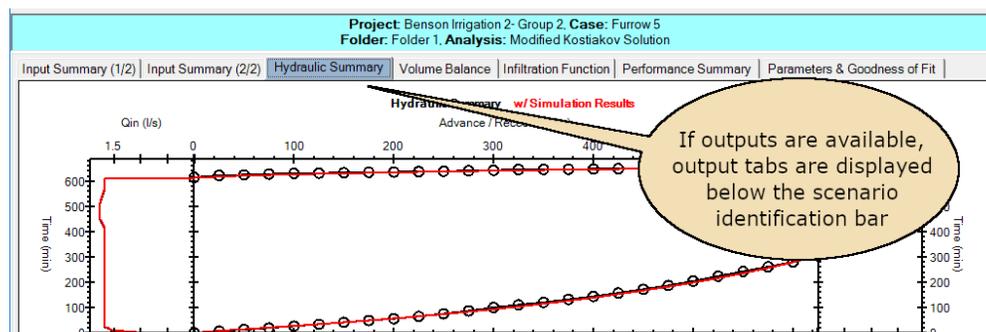


Figure 3.7: World Windows: output tabs

3.3 Data Organization and File Management

3.3.1 Data organization

From a programming standpoint, all WinSRFR data structures are objects. All objects are organized hierarchically in memory, using the structure illustrated in Figure 3.8. The top level of this hierarchy is a Farm (Project). A Farm object holds one or more Fields objects

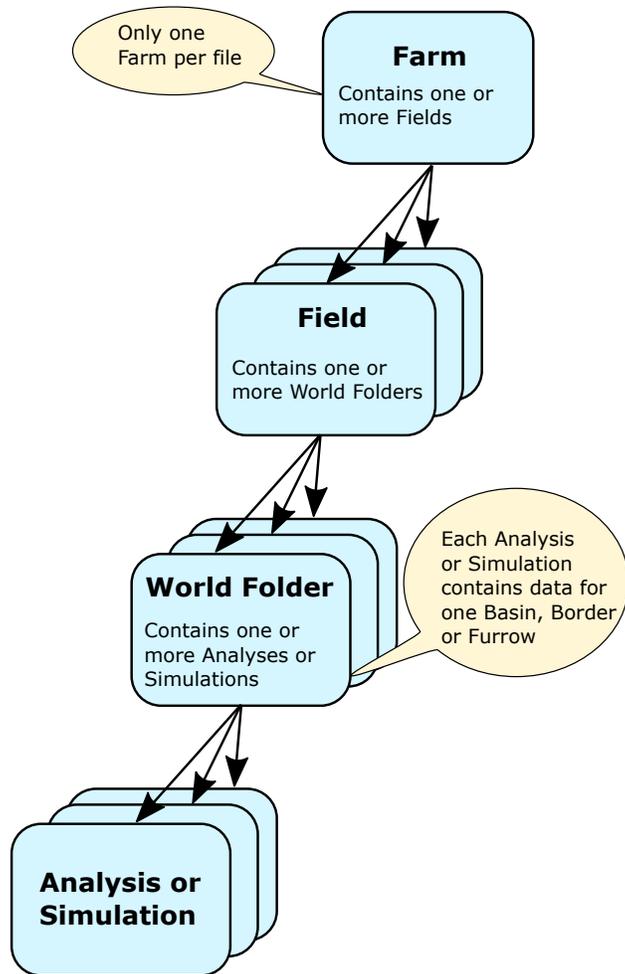


Figure 3.8: Data object hierarchy

which in turn, hold one or more World Folders. World folders can only contain specific types of scenarios. Thus, Event Analysis scenarios can only be created in an Event Analysis folder, simulations in a Simulation folder, etc. New scenario objects can be instantiated from existing scenarios using copy and paste. All data structures within a scenario are copied and pasted, even data that may not be supported in the new analysis World. For example, the Simulation World supports tabulated cross section data while the Event Analysis world does not. If a scenario from the Simulation World is pasted into an Event Analysis folder, the tabulated cross section is included but is not used by the Event Analysis World. After pasting a scenario from one world into another, the user will need to check the pasted data and edit original inputs that are not supported in the new world.

As in the case of information stored in memory, WinSRFR stores project data to a .srfr file hierarchically. In addition to storing input and output data set for individual scenarios, a .srfr file stores data needed to recreate all project objects. The file is not viewable or editable without the WinSRFR user interface and files can be very large, even with a small number of scenarios.

3.3.2 File management, compatibility, recovery, and size

WinSRFR uses conventional File management commands (*New, Open, Close, Save, Save As*) (Figure 3.9). When using the Open command, WinSRFR automatically resets the default directory data file path to the location of the mostly recently opened file, unless a file is opened from either the Examples or the Recent Projects Files list.

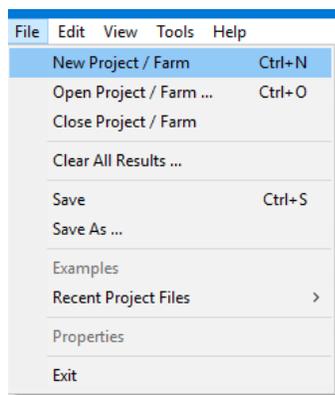


Figure 3.9: File management commands

Because of the hierarchical structure of the data, and the fact that new data structures have been added to objects as the software has evolved, WinSRFR data files are backward but not forward compatible. When opening a file created with a previous version, the new unused data fields will be populated with default values.

When saving a project, WinSRFR creates a backup file (with the extension name *.sfbk*) in the directory of the current project. This file can be used to recover an existing project if the file gets corrupted, but data added to a project since the last save operation will be lost.

File corruption problems have been noted when saving large project files. Thus, when dealing with large projects, it is advisable to reduce the file size prior to saving using the *File/Clear All Results command*. This command will clear all results and associated data structures, but preserve all input data including execution settings. If a fatal exception occurs while working on a project, WinSRFR generates a diagnostic file. The default location for that file is a subdirectory of the installation folder. The user can use the User Preferences to change the location of this diagnostic file. Please provide a copy of this file when contacting the developers to report a fatal exception.

3.4 Tools

The Tools menu in the Project Management Window provides access to these program features:

- **Data Comparison Tool**
- **Conversion Chart**

3.4.1 Data Comparer

The **Data Comparison Tool** (Figure 3.10) is used to compare results from different scenarios. The tool is launched with the *Tools/Data Comparison* command or by pressing F6

and has three sections. The top-left section is used to select the data types to be displayed using the provided checkboxes. Note that in this section the **Goodness-of-Fit** checkbox is used to compare data from Event Analysis and Simulation scenarios (field observations vs. predictions). The metrics used for comparison are the same ones used to verify Merriam-Keller analysis results, in the Event Analysis World. The **Data Explorer** is used to select the scenarios to be displayed. It replicates the structure of Analysis Explorer for the project. Scenarios with valid outputs are identified with checkboxes and, therefore, only those scenarios can be selected. Scenarios without outputs or with invalid outputs are displayed with a status icon (like the ones used by the Analysis Explorer). Results are presented in the tabbed pages, on the right-hand side of the form.

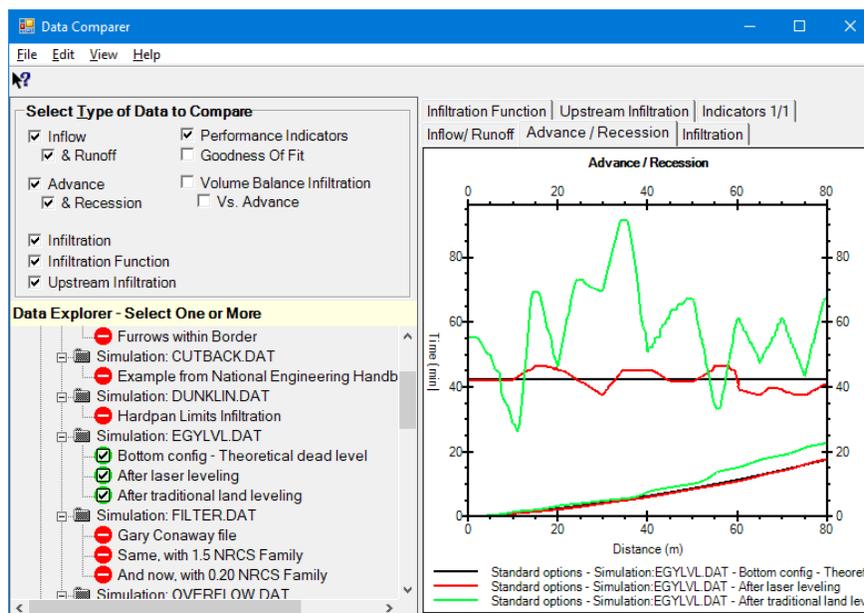


Figure 3.10: Data comparison tool

The sequence of colors used to display different series is user-selectable. Use the *Edit/User Preferences /Color* command to edit this color scheme. As explained in the Data Exchange section, all graphical outputs can be copied and pasted to other applications as bitmaps using the clipboard. They can also be exported to a file using various graphical formats. The underlying numeric data can also be exchanged using the clipboard. All results can be printed using menu commands.

To clear selections, uncheck the corresponding boxes in the Data Explorer. The menu command *Edit/Clear All Selections* un-selects all analyses.

3.4.2 Conversion Chart

The **Conversion Chart** (Figure 3.11) is used to convert units for individual values (*Tools/Conversion Chart* or F7). Conversions are provided for

- Length
- Area
- Depth
- Volume
- Flow Rate

Select the variable tab, enter the value in the appropriate unit input box, and press Enter to update the value displayed in other units.

LENGTH				
English			Metric	
1 ft =	1 yd =	1 mi =	1 m =	1 km =
0.305 m	0.914 m	1609.3 m 1.609 km	3.281 ft 1.094 yd	3280.8 ft 1093.6 yd 0.6214 mi
Feet	Yards	Miles	Meters	Kilometers
<input type="text" value="5280.0"/>	<input type="text" value="1760.0"/>	<input type="text" value="1.000"/>	<input type="text" value="1609.3"/>	<input type="text" value="1.609"/>

Length Area Depth Volume Flow Rate

Close

Figure 3.11: Conversion chart

CHAPTER 4

WORKING WITH THE GRAPHICAL USER INTERFACE

WinSRFR's Graphical User Interface (GUI) was developed using standard Windows controls, services, and conventions. This chapter discusses the GUI and its configuration options, the help system, and use of the Windows clipboard to exchange data with other applications. Users familiar with GUI controls and conventions in the Windows operating system can skip this chapter.

4.1 Visual and Navigation Elements

Windows forms and controls are the central GUI elements used to organize, display, and interact with the data. Program commands are issued using command buttons and/or the menu system. Users can navigate through the application using the mouse and/or keyboard commands.

4.1.1 Forms

The two main forms used by WinSRFR, the **Project Manager** and **World Windows**, were described in the previous chapter. The Project Manager is the parent form for all controls used by the program, including World Windows. The Project Manager can be moved within the display screen, resized, or minimized independently of open World Windows. Closing the Project Manager will close all open World Window forms and the application. The default size of the Project Manager and the World Windows can be set using the *View/Size*

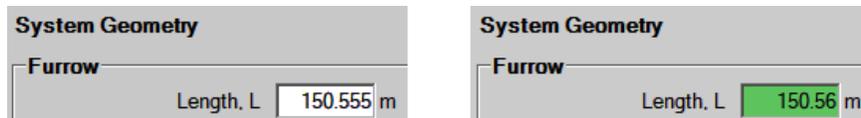


Figure 4.1: Input boxes and their effect on numerical inputs

command. This default size, saved in the registry, is used to optimally match the window size to the available display screen size.

Scenarios are opened using a World Window form. The form provides controls for data editing and validates the user-provided inputs. Only one World Window of each type (e.g., one Simulation World Window) can be opened at any time. World Window forms can be moved within the display screen, resized, and minimized.

Additional forms used by the application are launched from the Project Manager or from World Windows. These forms are used to define tabular inputs, modify program settings, or to display program outputs (such as the Data Comparison Tool). Many of these additional forms are modal, meaning that the user needs to provide the needed inputs and close the form before returning control to the parent form (a World Window or the Project Manager). Some of these forms cannot be resized or minimized, but all can be moved around in the display screen.

4.1.2 Data input and edit controls

WinSRFR input controls include input boxes, option buttons, check boxes, drop-down lists, and data tables. Use and limitations of input boxes and data tables is discussed next.

4.1.2.1 Input boxes

Input boxes are used mostly to enter numeric values. These controls are actually text boxes and display data using a format specified by the application. The format depends on the units typically used for the particular variable. As a result, the input boxes may not display data exactly as entered. For example, since the input box for field length displays only two significant figures, a field length specified as 150.5555 m will be displayed as 150.56 m (Fig. 4.1), but the data will be preserved in memory and file exactly as entered.

All numerical input boxes have a units label to their right (Fig. 4.1). The application will process those data based on the declared units. Units for the input boxes can be modified by right-clicking on the units label and selecting alternative units from the displayed menu. Manual conversions will be required if the data is available in units not used by WinSRFR. WinSRFR has a built-in unit conversion tool (invoked by pressing the function key F7 when viewing the Project Manager) that can assist with unit conversions.

4.1.2.2 Data Tables

Data Tables are used for entry and display of tabular data. They appear in Window's forms as well as in dialog boxes. Data can be entered manually, pasted from the clipboard or imported from a file. Tabular data can be copied to the clipboard and exported to a file.

The number of data table columns is determined by the number of variables required to define a particular input, for example field elevation as a function of distance. The maximum number of rows is user-defined. Depending on the data, some tables require either one or two rows of data at a minimum. The user cannot edit the independent variable (location or time) of those required rows of data, but only the dependent variable (e.g., field elevation, discharge).

Menu commands are used to add or delete table rows, as needed. Either form (Edit/Data table name) or context menus are available for this purpose. See page 43 for a description of context menus for data tables. Tab or Arrow keys are used to navigate through the cells in a data table.

The process of importing tabular data into WinSRFR is illustrated in Fig. 4.2. The file to the left (a .txt file) contains data ready to be imported into an elevation data table, which is displayed to the right. Data columns in the .txt file are tab-separated. The first line in this file displays the units applicable to each column of data. If this line is present, those units will be used when the data is imported. If this line is missing, the units currently being displayed by WinSRFR will be used instead. (In this example, the unit label line is redundant because the data is given in meters and the table is expecting values in meter). Unit labels recognized by WinSRFR are listed in Table 4.1.

The data can be imported by copying the data from the .txt file (Ctrl-C) to the clipboard and then pasting into the WinSRFR table, using the corresponding context menu (Right-Click, Paste Table). Alternatively, the *File/Import From File* command can be used. The application will stop an import operation if there are more columns in the imported data set than in the data table but will proceed with fewer columns in the data set than required. In the latter case, the application will then enter the available data in the first column of the data table and zeros for the missing data. The application determines the number of rows needed by the data table to handle the available data. Blank rows will be ignored. Error message(s) will be displayed if the data is not valid or incompatible with the current setup, such as when a data row is incomplete.

Data can also be imported from spreadsheets and other applications capable of creating tab-delimited files, but only using the copy/paste mechanism, or by saving the data as a tab-delimited .txt file. As in the previous example, a spreadsheet can be provided with a line to identify the units corresponding to each data column. Especially when working with large data sets, users will find that the capabilities of the built-in table control are limited and that it is more practical to edit the data with a spreadsheet.

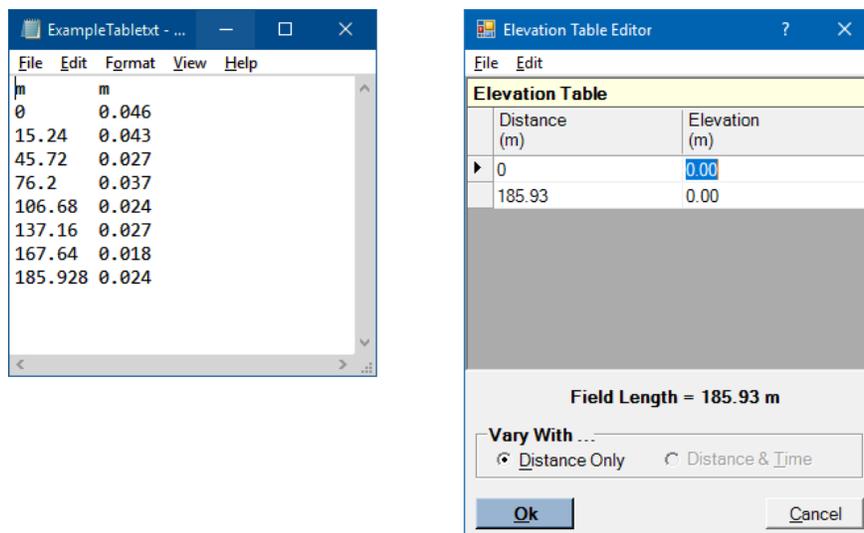


Figure 4.2: Importing data from a text file to a data table using the Windows clipboard

Table 4.1: Unit labels for importing tabular data

Length	"m", "ft"
Depth	"m", "mm", "cm", "in", "ft"
Side slope	"H/V"
Slope	"m/m", "m/100m", "ft/ft", "ft/100ft"
Time	"s", "min", "hr"
Flow rate	"cms", "lps", "lpm", "cfs", "gpm"
Percentage	"%"
Soil water holding capacity	"mm/m", "in/ft"

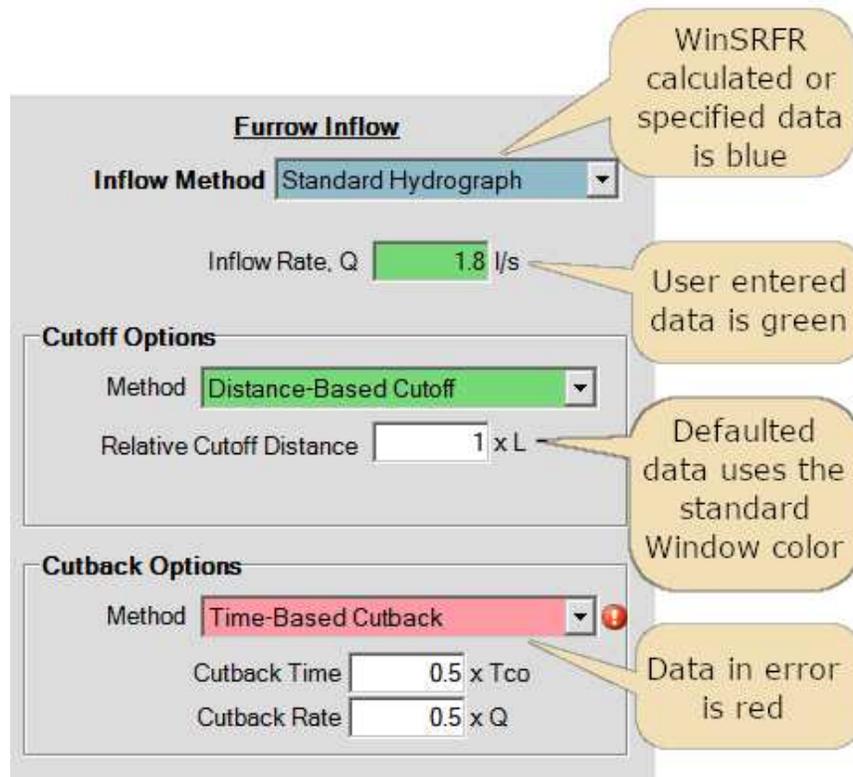


Figure 4.3: Color coding of data controls

Tabular data can be exchanged between scenarios using copy-and-paste, or by exporting to a .txt file and importing back into the target WinSRFR scenario. The export command also provides a mechanism for creating a data template in a text editor or a spreadsheet. Note that data files created by an export operation contain additional header information relative to the example of Fig. 4.2. That additional information is ignored during an import operation.

4.1.2.3 Color coding of data controls

The background color of text and drop-down input boxes identifies the source or condition of the data (Fig. 4.3). Scenarios created with the Start New Analysis command are populated with default values for all variables. Default values are identified with the standard Window background color. The controls will display with a green background when populated with user-provided data, but in blue when the data is provided by the application. For example, Furrow Length is a Physical Design Word output and the corresponding input box is displayed in blue once a solution is available. Blue drop-down lists indicate that WinSRFR offers only one choice for that variable under the given conditions. An example is the **Solution Model** selection option (Simulation World/ Execution Tab/Solution Model) if the user level is Standard User. In this case, the control displays the simulation engine selected by the application. If the user level is Advanced, two options may be available and the selected

option will be shown in green.

User-selected options may be incompatible with other user-selected options or with program- defaulted values. If these selections are considered by the application to be in error, they will be displayed in yellow or red, sometimes with an adjacent red icon. Hover the mouse over the red error icon next to the input control to display a tool-tip describing the error.

4.1.2.4 Undo/Redo

The *Edit/Undo* menu command allows the user to restore a scenario to a previous condition. The *Undo* command only works prior to execution of an analysis. Once the analysis is run, for example by pressing *Run Simulation* in the Simulation World, the sequence of inputs provided to the scenario is erased from memory. *Edit/Redo* serves to restore an input erased by an *Edit/Undo* command.

4.1.3 Menus and command buttons

WinSRFR uses a combination of command buttons and menus to issue commands. Command buttons are displayed in the background color of the form or in blue.

The WinSRFR menu system includes form menus and context menus. Form menus are always visible, such as the menus in the Project Manager and in a World Window. They are organized in logical groups, similar to those found in other Windows applications (*File*, *Edit*, *View*, *Help*, etc.). Context menus are hidden and are displayed by right-clicking on a particular control. Context menus are used by:

Analysis Explorer. These commands are used to edit the project data objects and to execute a simulation or analysis (Fig. 4.4). Different commands apply to folders (left image) than to scenarios (right image). A new feature in WinSRFR 5.1 is the ability to execute all scenarios contained in a folder, with the *Run All* command. *Run All* works with World, Case, and Project folders.

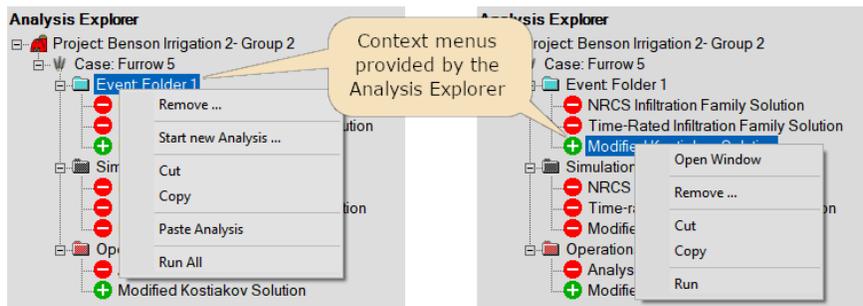


Figure 4.4: Context menu for the Analysis Explorer

Input boxes. (e.g., the **Furrow Length** input control, in the System Geometry Tab). The corresponding commands (Figure 4.5) are used to exchange data with the Windows Clipboard.

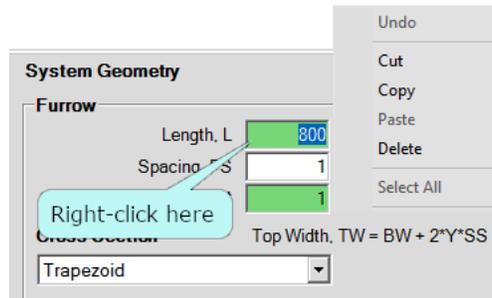


Figure 4.5: Context menu for a text box

Data entry tables. Two context menus are available for data tables (Fig. 4.6). The first is displayed by right-clicking on the upper-left corner of the data table and is used to exchange data with the Windows clipboard. The second is displayed by clicking on the left side of the table and is used to add or delete table rows, or to perform other actions, depending on the table.

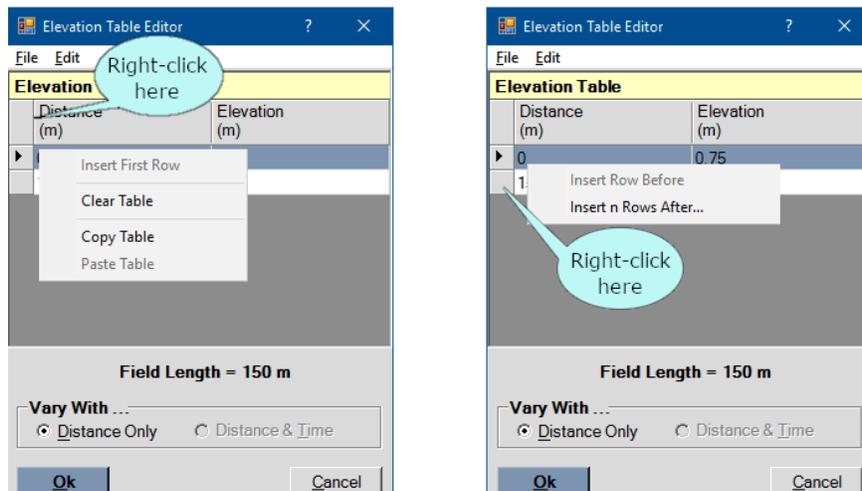


Figure 4.6: Context menus for data tables

Units labels. These menus are associated with input boxes (e.g., the units label for Furrow Length) are used to select a units system for displaying the data in the control (Fig. 4.7).

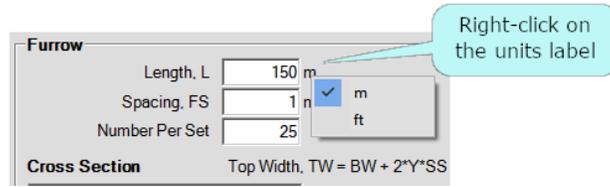


Figure 4.7: Context menus for unit labels

Graphics. These menus (Fig. 4.8) are used to copy graphical and numerical data to the Windows Clipboard. The images can also be exported to a file using different file formats. When viewing contours, a command is provided to select a solution point.

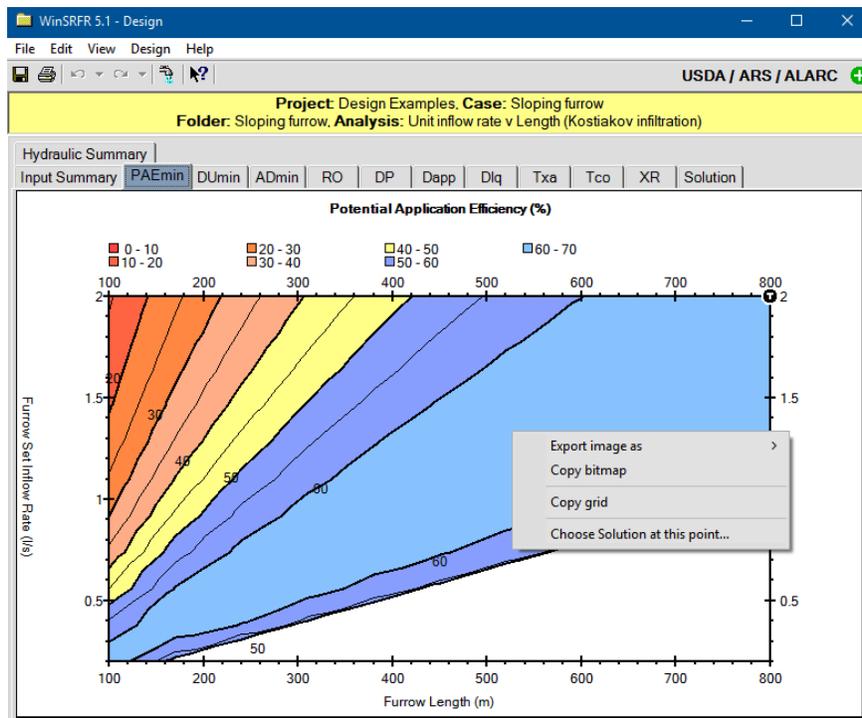


Figure 4.8: Context menus for graphical outputs

4.1.4 Output forms

Users can interact with output forms, first, by using menu commands to copy graphical outputs and the underlying data to external applications. Graphical format elements (colors, fonts) can be modified with the user settings, as described later. Last, in the case of graphs with multiple time- or space series, for example flow depth hydrographs, users can select which data series to display. This facilitates inspecting individual curves. Select a series to hide or display by left-clicking on the corresponding legend line (not the label) with the mouse while pressing on the Shift key. In Fig. 4.9, the output consists of 8 time-series (as indicated by the legend), but only three are displayed. When hovering over the legend with

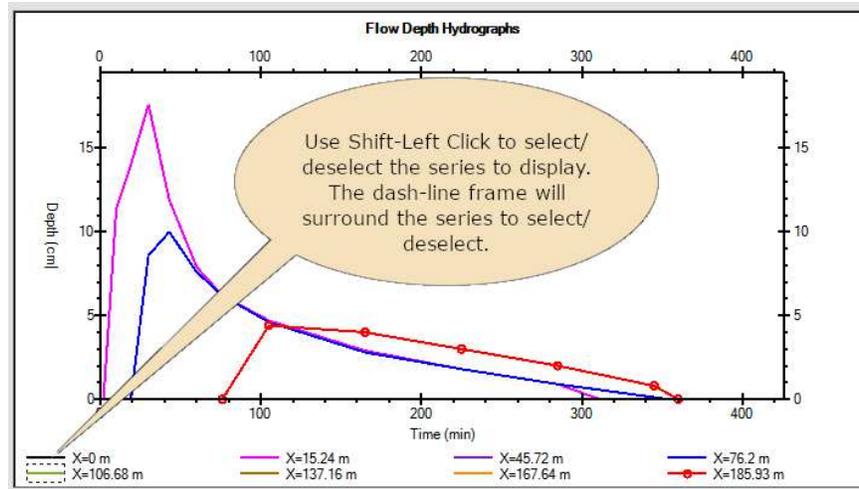


Figure 4.9: Selection of a series to display or hide in a multi-series graph.

the cursor, a dashed-line frame will surround the series to be selected. Individual series can also be selected using the *View/Select Series* command or using short-cut commands (Ctrl-Shift-F/N/P/L/A).

4.1.5 Navigation

WinSRFR allows users to interact with the application using either a pointing device (mouse) or the keyboard.

4.1.5.1 Mouse navigation

The application employs conventional mouse commands, e.g., a left-click pressed on a command button or menu item issues a command, pressing on a selection control (tab control, option button, check box, or drop-down list), enables that selection, while pressing on an input control or form will bring the focus to that form or control. A mouse right-click brings up a context menu, if one exists.

4.1.5.2 Keyboard navigation

Keyboard navigation requires a sequence of keyboard inputs to, first, select a control and, second, to perform an action with that control – edit its content, open its content, or execute an associated command. Commonly used commands are available through Function and Control key combinations. Keyboard navigation for different types of input controls is summarized in Table 4.2. Table 4.3 summarizes the use of Function/Control keys.

Table 4.2: Keyboard navigation for different types of input controls.

Menus
<p>Select. Press and release the Alt key. This selects the first menu in the menu bar and underlines the activation keys for all menu items.</p> <p>Click. Use the arrow keys (↑, ↓, →, ←) to traverse the menu to select the item you want then press the Enter key, or press the underlined activation key for the desired menu item.</p>
Tab Pages
<p>Select. Use the Tab key to move focus to the tabs. Use the arrow keys to select the tab page.</p>
Numeric Controls
<p>Select. To select a numeric input control, use the Tab key to move the focus to the control. Tab moves the focus forward while Shift-Tab moves the focus backward. Alternatively, use Alt as you would the Shift key to select the numeric control. Most controls have an associated activation key; this is the letter underlined in the control's label. For example, Alt-W will select the control with W underlined. The Tab key may be needed to select a particular control if it is in a group of controls that share a single label.</p> <p>Edit. When a numeric text box control has focus, its value is highlighted. Type in a new value in the control or use the arrow keys to position the cursor at the digit where the displayed value needs to be edited. Press Enter to enter the value and keep the focus on the control. Press Tab to enter the value and shift the focus to the next control.</p> <p>When using keyboard control, units labels cannot be changed!</p>
Drop-down lists and Option Buttons
<p>Select. Use the Tab key to move the focus to the control. Tab moves the focus forward while Shift-Tab moves focus backward, or use the Alt as you would the shift key to select the control. Most controls have an associated activation key; this is the letter underlined in the control's label. For example, Alt-S will select the control with "S" underlined. The Tab key may be needed to select a particular control if it is in a group that shares a single label.</p> <p>Edit. To edit the value of a selection control, use the arrow keys to move through the selections.</p>
Check Box Controls

Table 4.2: (continued)

Select. Use the Tab key to move the focus to the desired check box.

Edit. Use the Space bar to change the state.

Command Buttons

Select. Use the Tab key to move the focus to the button. Tab moves the focus forward while Shift-Tab moves focus backward or; use Alt as you would the Shift key to press the button. Most buttons have an associated activation key; this is the letter underlined in the button's label. For example, Alt-A will press the button with "A" underlined.

Execute. Use the Space bar to 'press' the button.

Analysis Explorer

Select. Use the Tab key to move the focus to the Analysis Explorer. Tab moves the focus forward while Shift-Tab moves the focus backward. Use the arrow keys to move around in the explorer. The ↑ and ↓ arrow keys move through the visible items. The ← key moves up through the items closing levels as it goes. The → key

Open Item. Once you have selected an Analysis or Simulation item, press the Enter key to display it in its corresponding WinSRFR World or Press the Space bar to display the context menu associated with the item. Use the arrow keys to select the context menu item then press Enter to activate that item. Press the escape key, Esc, to remove the Context Menu.

Table 4.3: Function and Control key commands

All Windows	
F1	Help
F5	Refresh display
Ctrl-X	Cut
Ctrl-C	Copy
Ctrl-V	Paste
Ctrl-S	Save
Ctrl-Y	Redo
Ctrl-Z	Undo

Table 4.3: (continued)

Results Tab	
Ctrl-F	Full page layout
Ctrl-G	Graphics layout
World Windows	
Ctrl-P	Print
Ctrl-R	Run the Analysis or Simulation
Ctrl-W	Display the main WinSRFR Project Management Window

4.2 User Settings

User settings modify the range of analytical options offered by the program, the display of visual elements, and the response of the application to certain user commands.

4.2.1 User level

The WinSRFR Simulation World offers many options for configuring irrigation systems. With the *Edit/User Level* menu command, users can restrict the options available for an analysis, and hence, those that are displayed on the user interface. Three user levels are available:

- Standard
- Advanced
- Research

This command is available only through the Project Manager Window. The setting is stored in the Windows registry and is saved for future sessions.

Most practical analyses can be conducted with the options offered at the Standard User Level. Advanced User Level options are less commonly used and some of those options require substantial knowledge by the user of the underlying computational procedures. Furthermore, some Advanced Level User options are still experimental. The Research User Level is available only for research and code development, and thus is not made available to the general public.

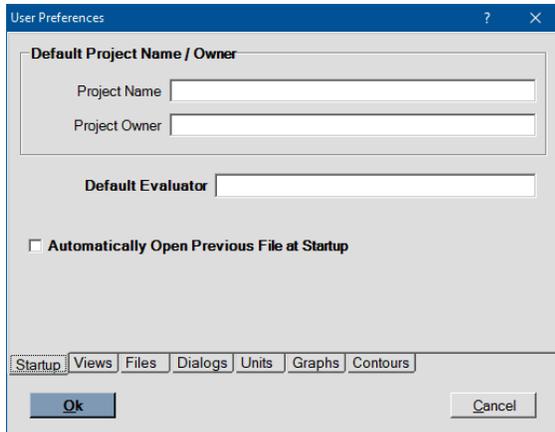


Figure 4.10: User Preferences dialog box

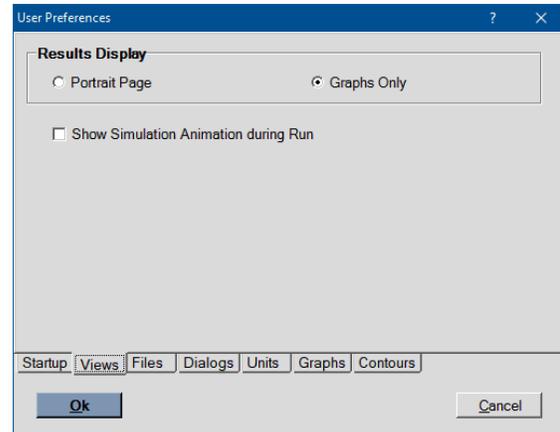


Figure 4.11: User Preferences/Views tab

4.2.2 User preferences

Users can set default values for the colors, fonts, units, etc. of the GUI using the Project Manager *Edit/User Preferences* menu command. These preferences are stored in the Current User section of the Window's Registry and can be set differently for different users sharing the same computer. New projects are created with these default options, but some of those options can be overridden for individual projects. Those particular settings are then stored with the project file.

4.2.2.1 Startup

The Startup tab (Fig. 4.10) is used to set:

Farm (Project) Name: Default name used when a new Farm / Project is created

Farm (Project) Owner: Default name used for the Farm/Project Owner

Evaluator: Default name of person running WinSRFR; used when a new Analysis is created

Open Previous File at Startup: If checked, reopens at startup the most recently opened file

4.2.2.2 Views

The Views tab (Fig. 4.11) displays the following options:

Results Display: Determines how graphical outputs will be displayed

Portrait Page: Both graphical and text outputs are displayed on a Portrait page (Print Preview-like view)

Graphs Only: Graphical outputs fill the available window; text outputs are displayed on a Portrait page

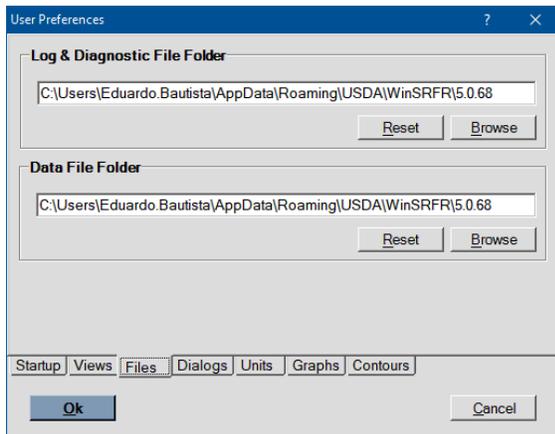


Figure 4.12: User Preferences/Files tab

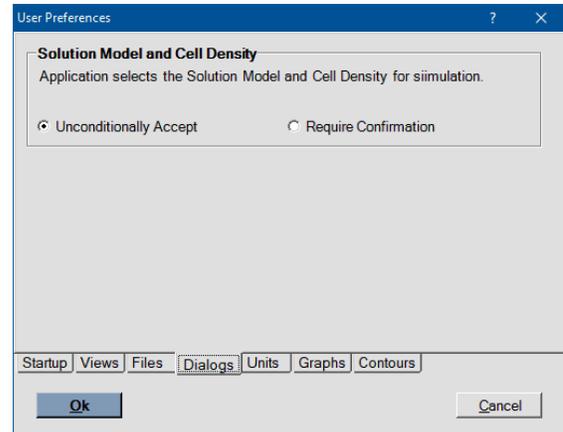


Figure 4.13: User Preferences/Dialogs tab

Show Simulation Animation: If checked, the **Simulation Animation Window** will automatically display when running a Simulation.

4.2.2.3 Files

File management options are set through the Files tab (Fig. 4.12):

- **Log & Diagnostic File Folder:** WinSRFR generates a file that helps diagnose some types of exceptions. This field contains the path to the log and diagnostics file. By default, the pathname is set to the folder provided by Windows for application data: C:\Users\...\AppData\Roaming\USDA\WinSRFR\5.1.
- **Data File Folder:** This field sets the path to the folder for WinSRFR's data files. As before, the default pathname is set to the application data folder. This is an obsolete option, as the program's opens its file manager at the last path used.

4.2.2.4 Dialogs

The Dialogs tab (Fig. 4.13) defines when and how some dialogs forms will be displayed:

Solution Model and Cell Density. When setting up a simulation, the application checks the inputs, determines which Solution Model and Cell Density are most appropriate for the given data, and sets values for those two simulation parameters. This option controls how these application-suggested inputs are handled.

Unconditionally Accept: Automatically accepts recommended values without confirmation

Require Confirmation: Prompts the user to verify the program- recommended selection for the simulation-engine controls.

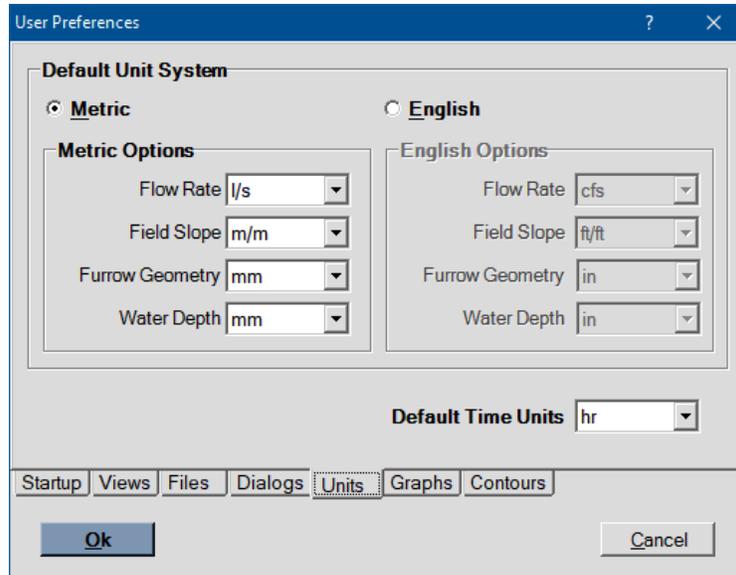


Figure 4.14: User Preferences/Units tab

The Solution Model and Cell Density parameters are explained in Section 6.1. For most applications, the user should allow the application to set these parameters. Thus, the recommended setting is **Unconditionally Accept**.

4.2.2.5 Units

Data stored in memory and in the `.srfr` file are in SI units; however, the user interface can be configured to display variables, in both input and output forms, in English or metric units (Fig. 4.14). Specific variables are displayed using units typically used in practice. For example, if working in English units, field lengths are displayed in feet and depths in inches.

- **Default Unit System:** Selects Metric or English as the default units system upon startup.
- **Metric/English Options:** Drop-down lists are provided for selecting units for Flow Rate, Field Slope, Furrow Geometry, and Water Depth
- **Default Time Units:** Selects hours (hr) or minutes (min) as the default time units

Two mechanisms are available for overriding the default units:

Setting units for the active project: use the *Edit/Units* menu item. This setting is stored in the project file. It does not affect the unit system of other WinSRFR projects or of new projects (which will continue to use the default system).

Setting units for individual inputs: use the context menu for individual input-item control. Numeric input controls that display units provide context menus to select the units for that individual input control. Right-click the mouse on the units label to display the context menu. These individual settings are not stored with the file and apply only to the current session.

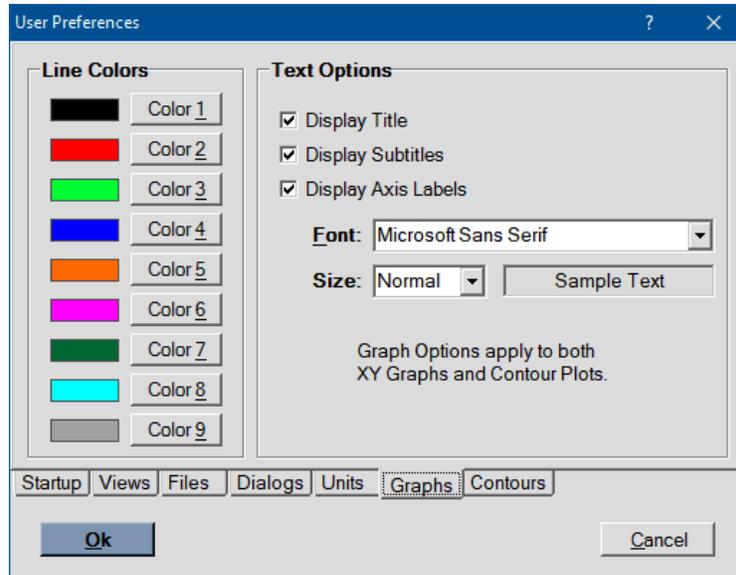


Figure 4.15: User Preferences/Graphs tab

4.2.2.6 Graphs

The Graphs tab (Fig. 4.15) controls the sequence of colors used to plot different data series. It also controls the display of the text in a graph.

Line Colors: Selects the color order of plotted data series

Text Options: Turns on/off the display of graph text (Title, Subtitles, Axis Labels) and selects Font type and Size.

4.2.2.7 Contours

The Contours tab (Fig. 4.16) sets default options used to generate contour graphs in the Operations Analysis and Physical Design Worlds.

- **Contour Fill Colors:** Selects the color scheme to use to fill the contour levels. The available options are an application-defined Color Scale, Gray Scale, User Defined color scale, and No Fill (only contour lines are displayed).
- **Contour Options:** Controls the display and calculation of various contour elements
- **Calculate Minor Contours:** Decreases the interval at which contours are calculated and displayed
- **Display Fill Color Key:** Turns on/off the display of a contour color legend
- **Display Contour Labels:** Turns on/off the display of contour labels
- **Display Grid Points:** Turns on/off the display of the contour grid points

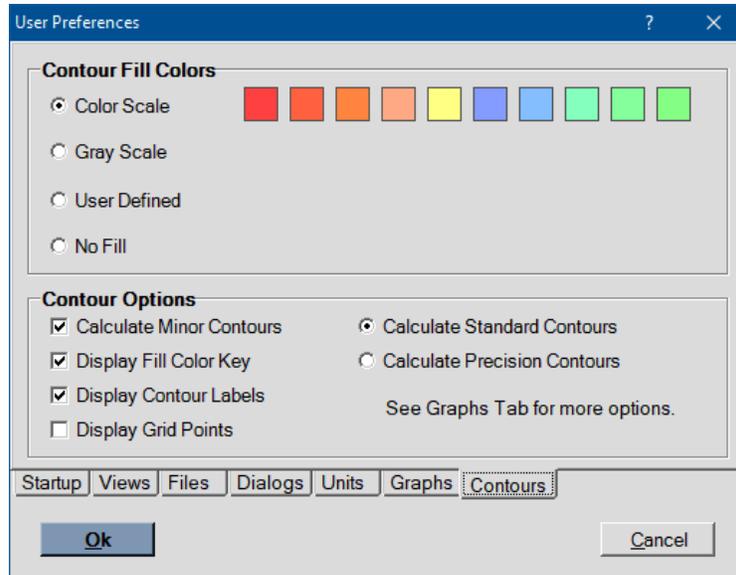


Figure 4.16: User Preferences/Contours tab

- **Calculate Standard Contours:** Selects low-order interpolation procedures for contour calculations
- **Calculate Precision Contours:** Selects high-order interpolation procedures for contour calculations

For individual projects, options that affect the calculation of contours can be overridden in the Execution tab of the Operations and Design Worlds.

4.2.2.8 Nomenclature Defaults

Use the *Edit/Nomenclature* menu command to select nomenclature used to refer to the two top level data containers displayed by the Analysis Explorer. The available choices are

- *Farm/Field*
- *Project/Case*

4.3 Help and Application Messaging

Guidance in the use of this software is provided through a Help system. In addition, using a Messaging system, the application provides feedback to the user in response to inputs or to conditions imposed on a scenario.

4.3.1 Help

The WinSRFR Help System provides general and context-specific help for its forms and controls. Table 4.4 summarizes the Help System mechanisms:

Table 4.4: WinSRFR Help System

PDF Manual	The PDF manual can be viewed at any time by using the Help/View PDF Manual command. Manual conventions and hyperlinking are explained in Section 1.9.
Help menus	General help and some context-sensitive help can be accessed through Help menu commands. Example of general help is help for working with the user interface.
F1 Key	Pressing the F1 key displays context-sensitive help for the form or tab page that has focus. When requesting help for a modal form (e.g., Elevation Table Editor), the help file has the program focus. This prevents any interaction with the modal form and the application. Close the help file to restore the focus to WinSRFR.
Help Button	Most dialog boxes have a Help button in the upper right corner.
What's This?	This help is activated by selecting the Help/What's This? menu command or by clicking on the What's This? toolbar button [ICON]. Clicking on a control (e.g., a tab page, a text box, etc.) provides information about the input required by that control.
Tooltips	World Windows display an error icon next to an input control if a problem is detected with the data. Tooltips provide information about the error and are displayed by hovering the mouse over the error icon. In the example, the message is that the entered value is negative.

4.3.2 Error and warning messages

Incorrect or inconsistent inputs inevitably lead to computational incidents or at least to faulty results. WinSRFR tries to prevent computational incidents by identifying suspect data. Computational incidents can occur with apparently valid and consistent inputs, if the application cannot handle the flow conditions defined by the data. If an incident occurs, or if peculiarities in the inputs or outputs are detected, the application provides diagnostic information which may help correct the problem.

4.3.2.1 Data entry errors

Input boxes and tables provide a first level of data validation and error messages. The application rejects inputs if the data type is incorrect (e.g., entering text values in numeric fields). If the input provided to a numeric input box has no physical meaning (such as zero or negative values for data that can only have positive values), the background color of control will turn to red and an error icon will appear next to the control. A tooltip can then be used to display an error message. The application may also trap data that is inconsistent with other data items. For example, entering a table of distance and field elevations with a field length that is not compatible with the value given in the Furrow or border length text box will generate an error message. These errors will prevent an analysis from executing.

4.3.2.2 Setup errors and warnings

Setup Errors and Warnings are displayed in the Execution or Verify Tab, prior to running an analysis.

Setup errors: Assuming that a Data Entry Error is not immediately corrected and the user changes the focus to the Execution or Verify tab, a setup error message will be generated. Data tables do not always generate Data Entry Error messages. In addition, inputs may be incomplete or incompatible. All inputs provided for a scenario are validated when the user switches to the Execution or Verify tab, or attempts to run the analysis (by pressing CTRL-R). At that point, those incorrect or incompatible inputs generate a Setup Error message. Figure 4.17 is an example error message generated with the EVALUE procedure, in the Event Analysis World. The error is the result of incompatible data. In this case, the application is expecting the final recession time at a station to match the recession time entered in the Advance/Recession tab page. The [Verify and Summarize Analysis](#) button will not be enabled until this error is cleared.

Warnings: These messages are generated prior to execution when an analysis can be executed with the given inputs, but the application detects potential anomalies with the data. Such would be the case of the second message displayed in Fig. 4.17. In this case, the analysis involves an open-end system, but no runoff data has been provided. A verification simulation can be run under these conditions, but those results cannot be compared with measured data.

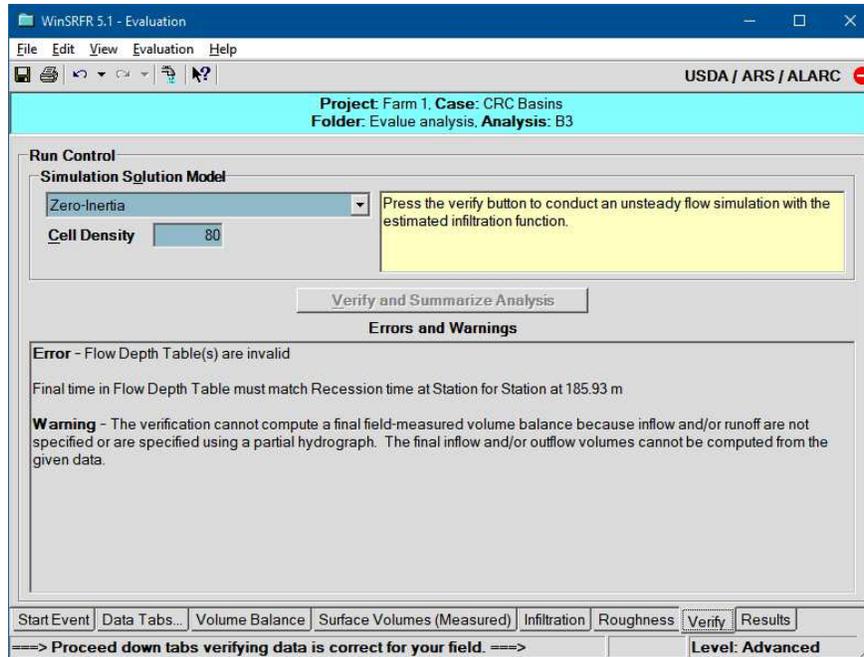


Figure 4.17: Example setup error and warning displayed by the Event Analysis World

4.3.2.3 Execution errors and warnings.

Execution errors A WinSRFR analysis involves the application of numerical methods and requires numerous calculations. A given set of conditions can result in a computational incident – for example calculation of a negative flow area or a failure to converge. Extensive exception-handling routines are built into the WinSRFR simulation engine and other computational procedures. Some of those routines allow the application to re-initiate the calculations after making numerical adjustments. The application provides no feedback to the user when the exception is resolved and computations are completed successfully. If the application is unable to correct the problem, calculations stop and an Execution Error message is displayed. The error-handling routines provide diagnostic information about the error. Rarely does an exception cause an unexpected program termination but in those cases an error file is generated.

Outputs generated by the application may still be available to the user, but only to the point where the exception occurred. Those available outputs will be displayed by the application. For example, if an exception causes a simulation to terminate, partial simulation results can still be viewed through the Simulation Animation Window.

Execution warnings Setup Warnings are redisplayed in the output summary screens as Execution Warnings, to remind the user of data peculiarities and the need to interpret results carefully. Other Execution Warnings are generated when results violate a constraint. For example, results are questionable when simulated flow depths exceed the specified maximum furrow depth. The simulation engine avoids a computational incident, but, without a warning, the user may fail to note the problem.

4.4 Data Exchange

WinSRFR supports data exchange using cut/copy/paste and import/export:

Within a Single WinSRFR Project To move data within WinSRFR, use the cut/copy/paste commands to copy and paste entire Fields, World Folders or individual Analysis/Simulation Objects.

Between Two WinSRFR Projects: To exchange data between WinSRFR data files, run two instances of the WinSRFR program and open the two files of interest. Use the cut/copy/paste commands to copy and paste entire Field or World Folders or individual Analysis/Simulations.

With Other Windows Applications Cut/copy/paste commands can be used to copy tabular data from a text file or spreadsheet to WinSRFR, or from WinSRFR to spreadsheets/text editor software (see section 4.1.2.2). These commands can also be used to copy WinSRFR graphical outputs to Windows applications that accept bitmaps, gifs, tiffs, etc.

Part II

Working with Scenarios

BASIC IRRIGATION SYSTEM PROPERTIES: COMMON INPUT TABS

Basic irrigation system properties are defined using the first four World Window tabs, namely:

- **Start**
- **System Geometry**
- **Soil/Crop Properties**
- **Inflow/Runoff**

These four tabs, referred to as common input tabs in this manual, are discussed in the following sections. Hydraulic Resistance and Infiltration (**Soil/Crop Properties** tab), are described in separate sections.

5.1 Start

Figure 5.1 illustrates the **Start** tab for the **Simulation World**. **System Type**, **Required Depth**, and **Unit Water Cost** are inputs required by all Worlds, to be explained in the following paragraphs. Below the common inputs are analytical options specific to each World. World-specific options are explained in chapters 6-9.

System Type: All analyses begin by defining the irrigation **System Type**. This selection determines the range of options displayed in the **System Geometry** and **Soil/Crop Properties** tabs. The remaining data tabs do not need to be edited in any particular order. The available choices are:

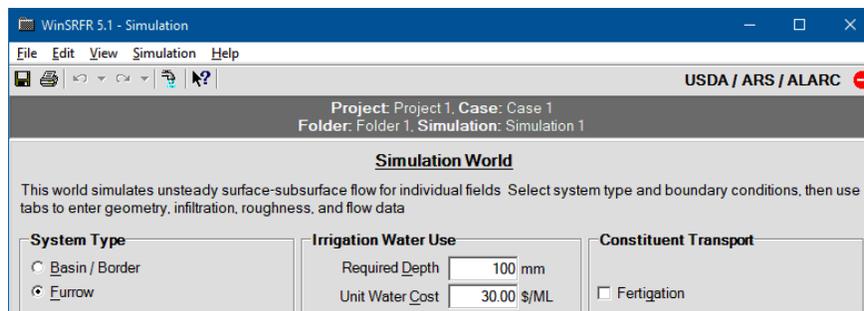


Figure 5.1: Start Tab: System Type and Irrigation Water Use panes

Basin/Border: Systems in which a field is divided into wide strips separated by berms or dykes. The field elevation fall across each strip is zero or small in comparison with the fall in the direction of flow. With basins/borders, the cross section is always rectangular and the flow is wide and shallow. More importantly, Since the flow top width is many times greater than the flow depth, infiltration is assumed one-dimensional.

Furrow: Systems consisting of a series of evenly-spaced narrow channels, with a trapezoidal or parabolic flow cross-section. In comparison with borders, the flow top width is narrow and of similar magnitude as the flow depth, Since lateral flow contributes significantly to the infiltration process, infiltration is assumed two-dimensional.

Irrigation water use: This section defines the depth of water to apply and cost (optional input).

Required depth: The Required Depth is the depth of infiltrated water needed to replace the soil water deficit. This target is used to calculate the amount of water that is stored in the root zone at the end of an irrigation event, the amount lost to deep percolation, and performance indicators depend on those two values. Event Analysis and Simulation World calculations can be carried out without properly defining the Required Depth, but performance measures that depend on this value will be meaningless. Operational and Design analyses cannot be executed without first defining a Required Depth.

Unit water cost: The unit water cost is used to calculate the total cost of applied water for an irrigation event. This input is not required for hydraulic calculations, only as supplementary information.

5.2 System Geometry

The geometry of an irrigation system is defined by its dimensions (length and cross-section), and bottom description. Border/basin geometry is defined differently from furrows. Most geometry configuration options apply to all Worlds.

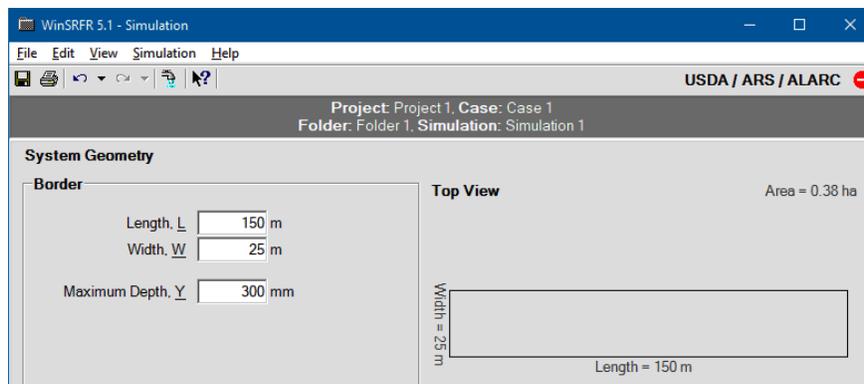


Figure 5.2: System Geometry tab: borders

5.2.1 Border/basin geometry

Inputs required to define the dimensions of basins and borders, are shown in Fig. 5.2:

Length: Length of the system in the direction of flow. Current WinSRFR procedures assume one-dimensional flow. Thus, they are most applicable to rectangular irrigation sets (borders, basins, and furrow sets). In practice, irrigation units are often not rectangular, but procedures for extending the one-dimensional analysis to two-dimensional systems have not yet been developed. At this time, when dealing with trapezoidal irrigation units, we recommend entering the average, and testing the results using the minimum and maximum field lengths. This input box is not user-editable in the Design World, because field length is an output of the analysis. It initially displays the message TBD (To Be Determined). This is updated after the design produces a set of results.

Width: This is the breadth of the system, perpendicular to the direction of flow. Besides determining the inflow rate per unit width in a border/basin, this variable is also used to compute the average infiltrated depth (infiltrated volume/unit length/unit width). The Border Width control is disabled in the Design World if the selected design option is to compute the Length and Width of the system for a given inflow rate.

Maximum Depth: This is the maximum depth of flow, defined by the height of the basin/border berms. This parameter has no effect on WinSRFR calculations¹, but the application issues a warning when the computed flow depth exceeds this value because the calculated performance measures are unreliable. Results may still be useful, if the overflow condition lasts for a relatively short time. Use the **Simulation Animation Window** to inspect the evolution of the surface flow profile in relation to the given Maximum Flow Depth.

¹The simulation engine allows the calculations to continue by extending the channel vertically.

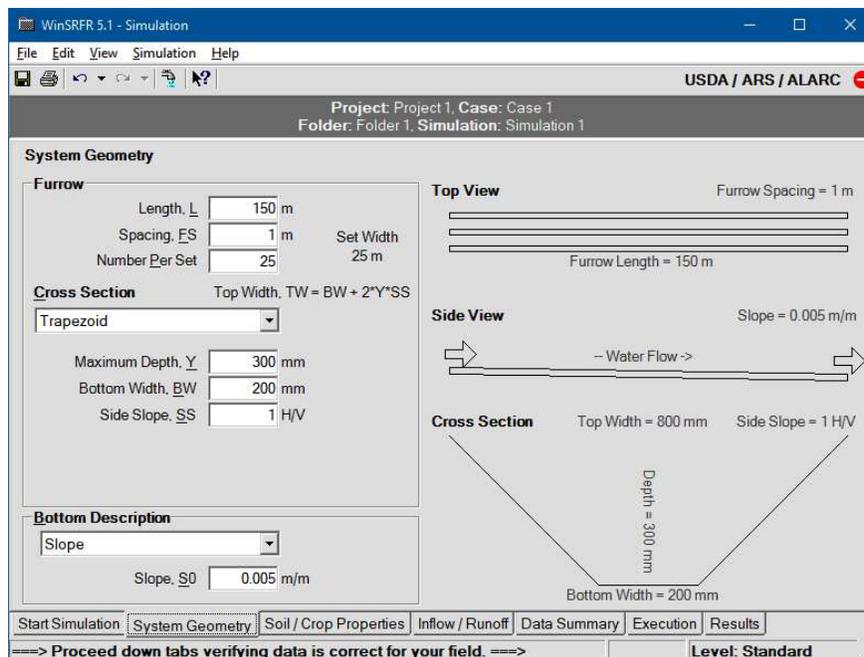


Figure 5.3: System Geometry: furrows

5.2.2 Furrow geometry

Figure 5.3 displays the **System Geometry** tab for furrows. The main difference with respect to borders is the definition of the flow cross-section.

Length : Length in the direction of flow. See comments for border length.

Spacing: This is the distance between furrow centers. Furrow spacing is used to compute the average infiltrated depth (volume/unit length/unit width) in the irrigated field. Thus, when modeling a furrow system in which every other furrow is irrigated, twice the nominal furrow spacing should be entered, to calculate a representative average application depth

Number per set: This input is the number of furrows in an irrigation set and must be given as an integer value. WinSRFR divides the total inflow rate by the number of furrows per set to obtain the unit inflow rate q_{in} (inflow per furrow). Ultimately, all hydraulic calculations (simulation, event analysis, design, and operations analysis) consider a single furrow. This control is enabled or disabled in the Design World, depending on the selected design option.

Cross-section: This drop-down list is used to define the shape of the furrow. It offers the following choices:

Trapezoid: With a trapezoidal section, the flow top width TW at a given flow depth Y is given by the relationship

$$TW = BW + 2 * y * SS \quad (5.1)$$

where BW is the Bottom Width and SS the Side Slope (Horizontal/Vertical). Relationships for flow area, wetted perimeter, and hydraulic radius follow from this definition. Input boxes for the two parameters, BW and SS , will be displayed (Fig. 5.3) when the Trapezoid option is selected. Also, the application will update the **Cross Section** graph, shown on the bottom-right hand corner of the System Geometry tab.

Power Law: A power law (i.e., parabolic) section is defined by a relationship of the form

$$TW = C * y^M \tag{5.2}$$

where TW and y are as previously defined, and C and M are empirical parameters. The units of C depend on the units of y and TW while M is dimensionless. When this option is selected, the form displays controls for the top width value at $y = 100$ mm (4 in, if working in English units) and the exponent M will be used to compute C . The Cross Section graph is updated when making this selection. As with the trapezoidal section, relationships for flow area, wetted perimeter, and hydraulic radius follow from the top width definition.

Trapezoid from Field Data: This option allows the user to enter field data and calculate the corresponding trapezoidal section parameters. An **Edit Data** button will appear when this option is selected. Pressing this button will launch the **Cross Section Editor**, described below. After processing the data and closing the Cross-Section Editor, the calculated Bottom Width and Side Slope will be displayed in their corresponding input boxes.

Power Law from Field Data: This option launches the Cross Section Editor but fits the data to a power law.

Maximum Depth: The maximum flow depth, as defined by the height of the furrow walls. A warning will be issued if the computed flow depth exceeds this value. See comments for borders.

A typical furrow cross-section is irregular and does not conform exactly to the geometric choices offered by the program – trapezoid or power law. Furthermore, the cross-section may vary along the length of run. A pertinent question then is how precisely does the cross-section need to be described? Results are sensitive to the cross-sectional description when infiltration is wetted-perimeter dependent. Otherwise, the cross-section mostly affects the computed flow depths. See the infiltration examples discussed in Section 6.3.1.2

5.2.2.1 Cross-Section Editor

The **Cross Section Editor** (Fig. 5.4) is used to compute the furrow cross-sectional parameters from field-measured data. Calculations proceed as follows. The user first identifies the type of cross sectional data available for the analysis. This selection is made with the **Furrow Cross Section Data** input control. The program can handle either furrow width versus depth data (using the **Width Table** or **Depth/ Width Table** options), or transverse length versus depth data, in an X-Y coordinate system (**Profilometer Table** option). Next, the user

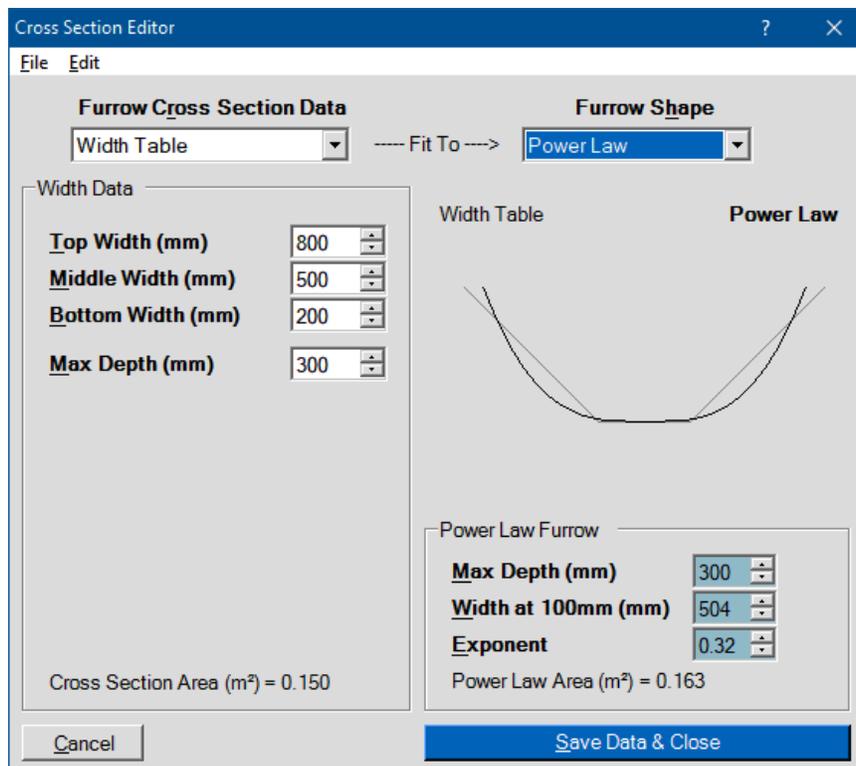


Figure 5.4: The Furrow Cross-Section Editor, illustrating the determination of cross section parameters from three width values

provides the cross-sectional data. Different input controls will be displayed depending on the Furrow Cross-Section Data selection. The data can be entered manually, imported from a text file, or imported via the Windows clipboard. The program automatically fits the data, based on the selected **Furrow Shape** (Trapezoid or Power Law). The program also displays, on the right-hand side of the editor (Fig. 5.4), a graph of the field-measured (thin line) and fitted cross sections (thick line). In the example, the given data are contrasted with a power-law fit. The computed parameters can be accepted at that point if the user is satisfied with the program-generated fit. If the fit is unsatisfactory, the user can test a different section with Furrow Shape, and/or manually modify the computed parameters (with the controls in the Parameters pane). Pressing the **Save Data and Close** button closes the dialog box, accepts the results, and transfers the computed parameters (and section type, if that option was changed) to the System Geometry Tab. Options vary depending on the selected **Furrow Cross Section Data** option and are explained next.

NOTE

The following paragraphs employ the term **DEPTH** to refer to the vertical distance from the furrow bottom to an arbitrary elevation. This definition, then, is equivalent to water depth within the furrow.

Width Table: This option (Fig. 5.4) requires the user to provide furrow widths (the trans-

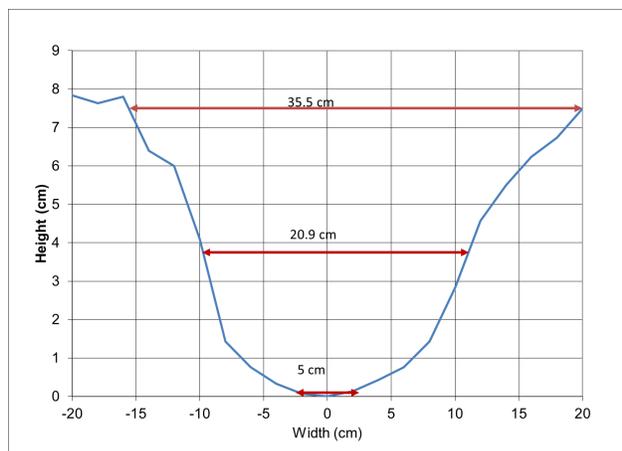


Figure 5.5: Furrow depth-width data.



Figure 5.6: Profilometer

verse cross-section length) at the bottom, middle, and top of the furrow. The input controls associated with these values are labeled accordingly in the Width data pane. **Max Depth** is the maximum flow depth entered in the System Geometry Tab. This is a practical way of characterizing the furrow cross section. Widths do not need to be measured with great precision if several data sets are collected along a furrow and averaged. Figure 5.5 illustrates three measurements of a furrow cross-section that do not exactly conform to a trapezoid or parabolic geometry.

Depth/Width Table: This option is similar to the previous one (Fig. 5.5), except that the user selects the number of data pairs (2 or more), and the depths at which the widths are given. This option should be used if the user has carefully measured depth vs. width data. For practical studies, measurements should be obtained at various locations and averaged. The dialog box displays a table for data entry.

Profilometer Table: A profilometer is used to measure distances from an arbitrary plane above the furrow to the furrow surface. These measurements are taken at multiple points along the furrow width in an X-Y coordinate system (Fig. 5.6). The application refers to the Y values as rod depths and the interval between X values as rod spacing. Profilometer data can be analyzed with this option. Analysis of profilometer data assumes an approximately symmetrical geometry, a coordinate system with the origin in the middle (X) and top (Y) of the furrow, and a constant rod spacing. Hence, X ranges from negative to positive values while Y values are only positive.

The data can be entered manually, imported using copy and paste, or imported from a file. The above described coordinate system needs to be employed when entering data manually. The number of measurements (No. of Rods) and the Rod Spacing need to be entered prior to entering the rod depths. Data can be imported with a different coordinate system, for example, with the origin at the left, bottom corner. The application will then make the necessary transformations.

Figure 5.7 is an example of a text file with profilometer data ready for import. In the example, the X values are given in inches and the Y values in centimeters, as indicated

in	cm
0	2
2	5.5
4	8.6
6	11.5
8	13
10	14.7
12	13.5
14	13.5
16	14
18	14.5
20	14.5
22	13
24	10
26	7
28	1.5
30	1

Figure 5.7: Text file with profilometer data.

Furrow Cross Section Data		Furrow Shape	
Profilometer Table		Trapezoid	
No. of Rods	13	Profilometer Table	
Rod Spacing (mm)	51	Trapezoid	
Profilometer Data		Trapezoid Furrow	
Rod Location (mm) *	Rod Depth (mm)	Max Depth (mm)	150
-306	5	Bottom Width (mm)	122
-255	38	Side Slope (H/V)	1.66
-204	77	Trapezoid Area (m²) = 0.056	
-153	115	Cross Section Area (m²) = 0.059	
-102	140	Cancel	
-51	155	Save Data & Close	
0	145		
51	148		
100	120		

Figure 5.8: Cross-Section Editor showing imported profilometer data.

by the column labels, and the X origin is at the left. If the rod spacing is not constant, the data will not import correctly. If the application fails to determine the correct rod spacing from the data, that value will have to be corrected manually in the Rod Spacing input box (Fig. 5.8). In cases where the Y data is inverted, the application will issue a warning, import the data, and convert it to a coordinate system compatible with its calculations.

5.2.2.2 Profilometer examples

The following examples are included in the Cross-Sections.srfr file and the Cross-sections.xlsx file.

Cross-section 1: The data for this example are illustrated in Fig. 5.9. Enter the raw data (with unit labels) into the profilometer data table. For this example, the profilometer had its horizontal scale marked in inches and the vertical one in centimeters. The data can be imported from a spreadsheet (or text file) in combined units if the table has unit labels in the first row. The software will issue a warning indicating that it cannot fit the data satisfactorily due to the irregularity of the data. From the photo and the plotted data, it should be clear that the right three points belong to the furrow bed. Eliminate the last three rows to make the data more symmetrical. The software will adjust the center of the furrow with the remaining data and find the best fit parameters. These data are equally well described by a parabolic or trapezoidal shape.

Cross-section 2: These data are more irregular than those Cross-section 1 (5.10). The furrow is clearly non-symmetrical. Enter the data in the table. The program issues a warning. Eliminating the last five points makes the more symmetrical, but the fit is

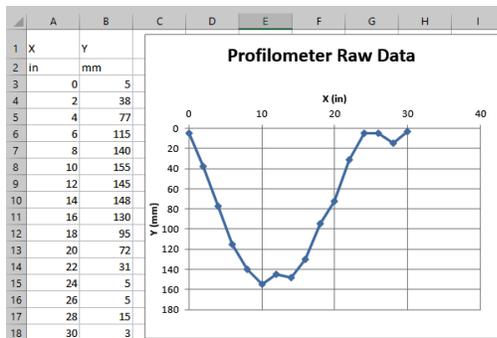


Figure 5.9: Data for example Cross-Section 1

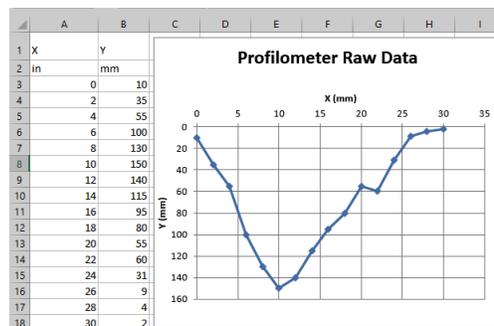


Figure 5.10: Data for example Cross-Section 2.

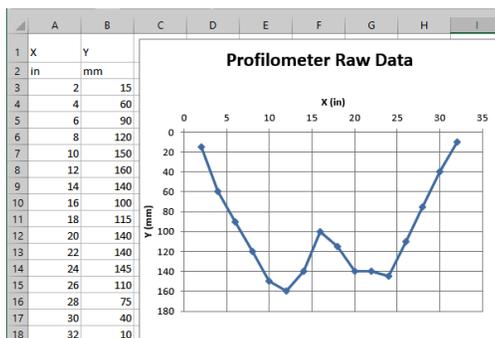


Figure 5.11: Data for example Cross-Section 3.

still not as good as with the example of the previous page. The data is better described by a parabola than by a trapezoid.

Cross-section 3: The raw data can be fitted to a trapezoid. This initial fit is identified in the SRFR file and the accompanying Excel file as Cross-Section A. The furrow has a hump in the middle and at small flow depths, this irregularity will cause substantial errors in the calculated flow area (Fig. 5.11). An approximate geometry can be developed by considering three separate flow sections and then fitting the resulting flow areas as a function of depth to a trapezoid. Calculations are explained in the Cross-sections.xls spreadsheet.

5.2.3 Bottom description

The **Bottom Description** drop-down control lists the options are available for describing the field bottom. They are the same for furrows as for basins/borders.

Slope: Use this option to specify a constant average field slope. The slope is entered as total vertical drop / field length or as total vertical drop per 100 units of field length (for example, in the U.S., it is customary to specify slope as ft/100ft). Use the units label to specify the unit system. Enter the slope value in the displayed input box .

Slope Table: Use this option to enter a table of longitudinal distances vs. slope. Press the [Edit Table](#) button to display the **Slope Table** dialog. The table requires at least one row of data, the slope at the upstream end of the field. Additional rows are locations where the slope changes. This option works in combination with the [Average from Slope Table](#) option, but only with Event Analysis and Simulation. In those Worlds, the field bottom can be specified with tabulated values or with the average value computed from the table. The Design and Operational Analysis Worlds only allow a constant field bottom slope.

Elevation Table: Use this option to enter a table of vertical field elevations as a function of distance. Press the [Edit Table](#) button to display the **Elevation Table** dialog. The table requires a minimum of two data rows, the elevations at the upstream and downstream ends of the field. The simulation engine interpolates field elevation at the points between survey stations. As with the [Slope Table](#), this option works in combination with the [Average from Elevation Table](#) option, but only for Event Analysis and Simulation.

Average from Slope Table: This option calculates an average slope from a table of slope values. It is provided to facilitate transferring scenarios with tabular slope data from the Event Analysis or Simulation Worlds to the Operations Analysis and Design World, as those analyses assume a constant average slope for the field. This option is available in all Worlds.

Average from Elevation Table: This option calculates an average slope from a table of elevation values. As with the previous option, it is provided to facilitate transferring scenarios with tabular elevation data from the Event Analysis or Simulation Worlds to the Operations Analysis and Design Worlds and is available in all Worlds.

5.2.3.1 Advanced Options

Basins/ Borders:

Tabulated: This option is available for simulation only. Check this box if the berm height is variable with distance. Use the Border Depth Table to specify the variation in maximum depth as a function of distance.

Border Depth Table. This table is displayed when the **Tabulated** box is checked. Maximum depth needs to be specified at least at the upstream end of the field. The application assumes a linear variation in depth between locations with a specified depth.

Furrows:

Tabulated: This option is available for simulation only. If checked, it enables modeling non-prismatic furrows. The application displays the [Cross Section Table](#) when this box is checked.

Cross Section Table: Use this table to specify variations in cross-sectional parameters with distance. Only one cross-section type (trapezoid or power law) is allowed. The application varies the cross-section in-between distances with a cross-section definition. The cross-section needs to be defined at least at the upstream end of the field. The **Cross-Section Table** can be used in combination with the **Cross Section Editor** to define cross-sectional parameters data at selected locations. To do this, right-click on the location for which geometric parameters will be calculated. Then, select the **Cross-Section from Field Data** option in the context menu. When specifying tabular cross-sectional data in combination with the Cross Section Editor, the software saves the resulting geometric parameters but not the input data for each location. Those inputs should be saved to a text or spreadsheet file if they are to be preserved for future use.

5.3 Soil/Crop Properties: Hydraulic Resistance

Hydraulic resistance is defined with controls in the **Roughness** pane, located in the **Soil/Crop Properties** tab. Available options depend on the user level.

The soil surface and submerged vegetation exert a resistive drag force on the flowing water. WinSRFR calculates this drag force as,

$$S_f = V |V| / C^2 R \quad (5.3)$$

In this expression, S_f is the friction slope, i.e. the resistive drag force divided by the weight of the stream, each per unit length of channel. Under typical surface irrigation conditions, S_f is equal to the slope of the water surface; it is proportional to the flow velocity V , and inversely proportional to the hydraulic radius R (area divided by wetted perimeter, a measure of their relative importance), and an empirical parameter describing the roughness characteristics of the channel, the Chezy coefficient C .

5.3.1 Standard options

The default method for calculating C in WinSRFR is with the Manning formula (Manning, 1891),

$$C = c_u R^{1/6} / n \quad (5.4)$$

in which the user provides a value for the empirical roughness coefficient n . The user can select n from a predefined list of values recommended by the USDA-NRCS surface irrigation design guides. Those values are displayed as option buttons (NRCS Recommended Value) in the Roughness frame. Alternatively, a locally calibrated value of n can be provided in the User- Entered Value input box.

The Manning n has dimensions of $[L^{1/6}]$, but the same numerical value is used when working in either English or metric units. Conversion to appropriate units is accomplished

with the constant c_u . This and other inputs are provided by the simulation engine as part of the calculations.

Typical calculations with the Manning formula assume that n encompasses the effect of soil-surface and vegetation drag on the irrigation stream. Large values of n imply a large friction slope and, therefore, large flow depths for the same flow rate. The value of n is assumed to be a function of the channel surface characteristics, and thus independent of flow rate and depth.

The Manning formula is used exclusively by the Event Analysis, Operations Analysis, and Physical Design Worlds, and is the only option available for Standard and Advanced Users in the Simulation World. Research-level users have access to more options.

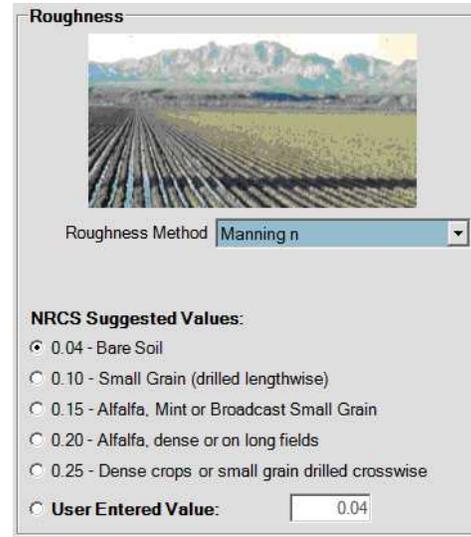


Figure 5.12: Calculation of hydraulic resistance with the Manning equation

5.3.2 Advanced options

Roughness Method - Sayre-Albertson: A method for calculating the Chezy C is with the logarithmic Sayre-Albertson relationship (Sayre and Albertson, 1961).

$$C = 6.06\sqrt{g}\log_{10}(R/\chi) \quad (5.5)$$

With this expression, the user needs to enter the absolute roughness of the soil surface, given by the variable χ (Fig. 5.13). Note that in contrast with the Manning n , χ needs to be specified in appropriate length units.

Tabulated: This check-box control (Fig. 5.14) allows the user to specify spatial variations in roughness with distance. This option can be used, for example, to model situations where there are substantial variations in vegetation density along the field. If enabled, the Roughness pane will display the [Roughness Table](#). This table is used to specify roughness coefficients for the selected resistance equation as a function of distance. When the Roughness Table is first launched, it displays a roughness coefficient at the field inlet (distance = 0). This value applies to the entire length of the field, unless a new roughness coefficient is indicated at a given distance. New values apply from the specified location up to the next roughness location or to the end of the field. The [Roughness Table](#) cannot be used in combination with the option buttons for specifying recommended values for the Manning n . Those values have to be provided manually.

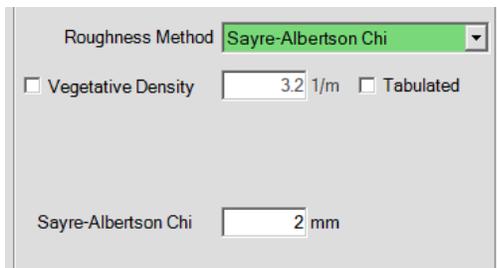


Figure 5.13: Modeling hydraulic resistance with the Sayre-Albertson equation.

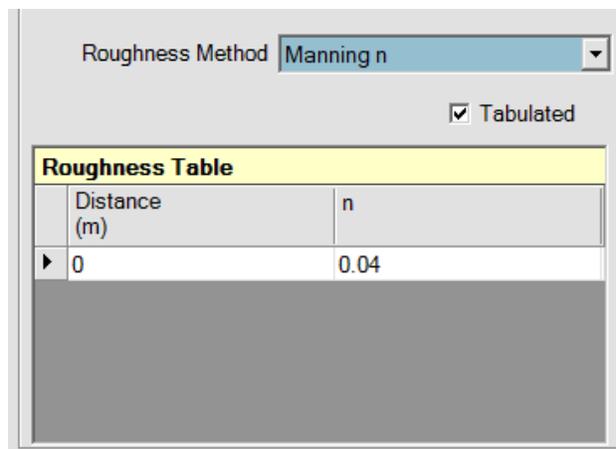


Figure 5.14: Modeling variable roughness with the Tabulated option.

5.4 Soil/Crop Properties: Infiltration

The infiltration process is defined with controls in the **Infiltration** pane, located in the **Soil / Crop Properties** tab. The configuration options displayed depend on:

- The system type (furrows vs. basins/borders).
- The World that the user is working in – The Event Analysis, Operational Analysis, and Design Worlds offer a limited set of configuration options in comparison with those available for the Simulation World. Infiltration is an output of Event Analysis and is not a configuration option.
- The User Level.

Infiltration is the process of water absorption into the soil. In a one-dimensional view of the irrigation stream, in which water advances uniformly across a symmetric channel, all variables are functions of distance along the field x and time t only. The pertinent infiltration variable is the volume infiltrated per unit length $A_z(x, t)$ [L^3 / L], which is symmetric at any distance x .

The function A_z is defined by selecting an infiltration modeling approach and then specifying the model parameters for the particular field. The infiltration configuration controls are displayed in the Infiltration block, on the right-hand side of the **Soil/Crop Properties** tab page (Simulation, Operational Analysis and Physical Design). Infiltration controls for the Event Analysis World will be discussed in Chapter 7. Infiltration modeling options offered by the software depend on the selected system (borders/basins vs furrows). The selected infiltration model determines how many input parameter boxes are subsequently displayed. Parameters must be provided in the units indicated next to the input boxes, but the units are configurable, as described in Section 4.2.2.5. The resulting infiltration function is displayed in the Infiltration block, as infiltration depth D_{inf} vs. time, to enable comparisons with the

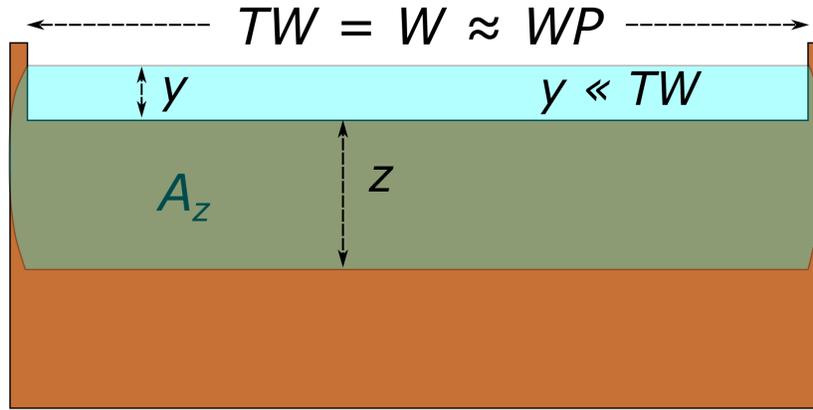


Figure 5.15: Infiltration in borders/basins

required infiltration depth. D_{inf} is given by the ratio A_z/W borders and by A_z/FS with furrows.

5.4.1 Border/basin infiltration

Figure 5.15 depicts A_z at a typical border cross section. The surface flow is wide and shallow (i.e., the flow top width TW is many times greater than the flow depth y). The stream-soil interface through which infiltration takes place – the wetted perimeter WP – remains nearly constant as a function of y and therefore, can be assumed to be equal to the border width W . Since most of the water infiltrates in the vertical down direction, lateral infiltration through the berms can be ignored. With these considerations, A_z is calculated as

$$A_z = z \cdot W \quad (5.6)$$

in which z is a depth computed with one-dimensional infiltration equation. The equation is selected with the **Infiltration Equation** drop-down control. Empirical and soil-physics based alternatives are offered by the software. Empirical equations calculate z as a function of the opportunity time $\tau(x)$ only, $z = f(\tau(x))$. The opportunity time is defined as the time that the water remains ponded on the soil surface. τ varies with distance along the field, and is determined by the simulation. Physically-based equations calculate z as a function of the hydraulic properties of the soil and the history of flow depths at any location, $z = f(y(x))$ and the resulting water pressures.

5.4.1.1 Empirical equations

Kostiakov (Kostiakov, 1932):

$$z = k\tau^a \quad (5.7)$$

This empirical equation models a declining infiltration rate with opportunity time τ . With this selection, the Soil/Crop Properties tab displays input boxes for the parameters k and a . Typical units for the constant k [L/T_a] are in/h^{*a*} or mm/h^{*a*}. The

dimensionless exponent a is restricted to $0 < a < 1$. This applies as well to variants of the Kostiakov equation, namely Eqs. 5.8, 5.10, and 5.12. The parameters need to be calibrated from field measurements.

Modified Kostiakov (Lewis, 1937; Strelkoff, 1990):

$$z = k\tau^a + b\tau + c \quad (5.8)$$

Soils typically exhibit a well-defined steady-state infiltration rate after some time. The Kostiakov equation, which predicts an ever-declining infiltration rate, represents this type of behavior inadequately. This shortcoming can be overcome by adding the product $b\tau$, where b [L/T] represents the long-term infiltration rate. That expression is commonly identified as the Kostiakov-Lewis equation. In many soils, a large volume of water infiltrates at short opportunity times through cracks and macropores. Once the macropores fill and/or close due to soil swelling, infiltration is controlled by the soil matrix and the infiltration rate decreases gradually. This behavior is difficult to model with either the Kostiakov or Kostiakov-Lewis equations. A rudimentary way of modeling macropore infiltration is to treat it as a fixed volume per unit area [L] that infiltrates instantaneously, represented by the letter c (Mailhol and Gonzalez, 1993). The resulting expression, Eq. (5.8), is the Modified Kostiakov equation. Eq.(5.8) in combination with Eq.(5.6) can be written as

$$A_z = (k\tau^a + b\tau)W + cW = A_{zSoil} + A_{zMP} \quad (5.9)$$

This notation emphasizes the two distinct flow processes represented by the equation, flow through the soil matrix A_{zSoil} (porous media flow) and flow through cracks and macropores A_{zMP} . As with the Kostiakov parameters, the parameters of Eq. 5.9, k , a , b , and c , need to be provided in consistent units and need to be calibrated from field data.

NRCS Infiltration Families (USDA-SCS, 1974;USDA-SCS, 1984):

$$z = k_{scs}\tau^{a_{scs}} + c_{scs} \quad (5.10)$$

The infiltration family concept categorizes soils with similar basic infiltration rate. The category (family) identifier is related to that basic intake rate measured in inches per hour. The families are represented by a modified form of the Kostiakov equation. The parameters k_{scs} and a_{scs} are fixed values, specific to each family, but c_{scs} is constant for all families (7 mm or 0.28 in. in English units). In contrast with the c parameter of the Modified Kostiakov equation, c_{scs} is a fitting constant and is not meant to represent infiltration through macropores. In fact, use of the infiltration families is not recommended in soils that exhibit macropore/crack flows (USDA-SCS, 1974).

The infiltration families were originally developed for border irrigation (USDA-SCS, 1974) and later adapted to furrows (USDA-SCS, 1984), as will be discussed later. Because of their similarity, WinSRFR uses the furrow families to represent both border

and furrow infiltration.

No parameter input boxes are displayed with this selection. Instead, a family number must be selected using option buttons. Parameters values will be displayed on the tab (without the subindices). While the parameters are not calibrated, field tests should be conducted to determine which family best represents a particular soil.

Walker et al. (2006) proposed a revised NRCS infiltration family concept. In contrast with the original families, the revised relationships were developed from furrow infiltration data, and then adapted to borders. Those families have not been adopted yet in WinSRFR.

Characteristic Infiltration Time (Strelkoff, 1990): This option is a variation of the Kostiaikov equation (5.7). It is based on the premise that a reasonable infiltration function can be derived from an estimate of the opportunity time needed to infiltrate a specified irrigation target, typically the irrigation requirement D_{req} (see Appendix C.1). The target depth and time are identified, respectively as the **Characteristic Infiltration Depth** (D_c) and the **Characteristic Infiltration Time** (τ_c). With the Kostiaikov equation, different combinations of k and a will predict the same (D_c) at (τ_c). If this option is selected, the Soil/Crop tab will display input control boxes for (D_c), (τ_c), and the exponent a . The parameter k is calculated by the program from Eq. (5.7) and displayed above the input control boxes. This option is available for Simulation, Design, and Operational Analyses, but not for Event Analyses (in which case the analysis yields simply the Kostiaikov parameters).

Time-Rated Intake Families (Merriam and Clemmens, 1985):

$$z = k_{mc}\tau_{100}^{a_{mc}} \quad (5.11)$$

This option, like the NRCS families, categorizes soils with similar infiltration behavior. The categories are defined by the time needed to infiltrate a Characteristic Depth (D_c) of 100 mm (4 in), identified as τ_{100} . Thus, this option can also be considered a variation of the Characteristic Infiltration Time concept. τ_{100} is the only required input and is specified using the **Characteristic Infiltration Time** input box. τ_{100} is used by the software to determine the constant and exponent k_{mc} and a_{mc} respectively. The Time-Rated Intake Families are available in all Worlds, but only for border/basin irrigation. Mathematical details are provided in Appendix C.2.

Branch (Clemmens, 1982):

$$z = \begin{cases} k\tau^a + c, & \tau \leq \tau_b \\ (k\tau_b^a + c) + b(\tau - \tau_b), & \tau > \tau_b \end{cases} \quad (5.12)$$

This variation of the Modified Kostiaikov equation allows the infiltration rate to suddenly stabilize at a specific opportunity time, known as the branch time τ_b . This modeling approach can be used to simulate textural changes with soil depth or the

presence of a compacted sublayer. The Branch Function, is available for Simulation and Event Analysis only. The parameters k , a , b , and c have the same meaning and dimensions as the parameters of the Modified Kostiakov equation. However, those parameters must satisfy the condition:

$$b \leq ka\tau_b^{a-1} \tag{5.13}$$

i.e., the steady infiltration rate must be less than or equal than the derivative of the transient infiltration at time τ_b . Eq.(5.13) is used as an equality when the lower horizon is more permeable than the upper one. In this case, the user needs to uncheck the **Branch Time** checkbox. The branch time τ_b will then be calculated from the given data. Eq.(5.13) is used as an inequality when the lower soil horizon is less permeable. In that case, the **Branch Time** checkbox needs to be checked and a value for τ_b needs to be provided in the corresponding input box.

Modified Feature!
Previous versions of WinSRFR did not handle the case where infiltration rate decreases at the branch time. This is new in WinSRFR 5.1.

5.4.1.2 Semi-physical and physical infiltration equations

Green-Ampt (Green and Ampt, 1911):

$$z = \tau K_s + \Delta\theta\Delta h \ln\left(1 + \frac{z}{\Delta\theta\Delta h}\right) \tag{5.14}$$

$$\Delta\theta = \theta_s - \theta_0; \quad \Delta h = y - h_f$$

This is an Advanced User Level option. The Green-Ampt formula was derived from porous media flow theory and calculates infiltration as a function of hydraulic properties of the soil, the initial water content, and the computed flow depth y (i.e., the pressure of water on the soil surface). This equation assumes that the soil is completely saturated behind the infiltrating water front, a homogeneous texture, a uniform initial water content, and a constant water pressure on the soil surface (i.e., flow depth). A modified form of this equation (Warrick et al., 2005) is used in WinSRFR to account for the variation of y with time. Parameters that need to be entered are:

Saturated Water Content, θ_s : This is the water content of the wet soil, expressed volumetrically (volume/volume).

Initial Water Content, θ_0 : Volumetric water content of the dry soil. Generally, this value will be somewhere between the water content at field capacity and permanent wilting point.

Wetting Front Pressure Head, h_f : Tension exerted by the soil at the boundary between the wet and dry soil, expressed as a pressure head (pressure/specific weight of water = length) Computationally, it is defined as the weighted average of the soil pressure vs. hydraulic conductivity relationship (Bouwer, 1964; Morel-Seytoux and Khanji, 1974; Neuman, 1976). Although technically a negative value, h_f is entered as a positive value.

Hydraulic Conductivity, K_s : Conductivity through the saturated soil profile [L/T].

Macropore infiltration, c : As explained above, the Green-Ampt equation represents only porous media flow. However, it can be combined with a macropore infiltration term c [L_3/L] (Clemmens and Bautista, 2009). As with empirical infiltration models, c is assumed to infiltrate instantaneously.

Soil Texture: Whenever possible, Green-Ampt parameters should be determined for the specific conditions using field data. In the absence of measurements, the Soil Texture drop-down control will display estimates for the parameters based on major soil textural categories, as reported by Rawls et al. (1983). The initial water content is the water content calculated with the Brooks and Corey (1964) water retention model and the Brooks-Corey parameters reported by Rawls et al. (1982) at a soil water pressure of -900 cm.

Richards (Richards, 1931):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial \zeta} \left(K(\theta) \frac{\partial h}{\partial \zeta} \right) + \frac{\partial K}{\partial \zeta} \quad (5.15)$$

This partial differential equation was derived from porous media flow theory. It treats infiltration as a diffusive process, meaning that the soil is assumed to be variably saturated behind the infiltrating water front. This is a more realistic representation of the infiltration process in comparison with the Green-Ampt equation, which assumes a fully saturated soil. Variables are: h = the soil water pressure head [L]; K = hydraulic conductivity of the soil [L/T], which varies with the volumetric water content θ ; σ the vertical distance in the soil profile, and; t = time. Since no closed-form solution is available for the Richards equation, solutions need to be approximated numerically. The inputs required for this Advanced User Level option are very different from those described in previous paragraphs. Thus, they are explained in a separate section in this chapter.

5.4.2 Furrow infiltration

In furrow irrigation, the flow top width and depth can be of similar magnitude (Fig. 5.16). As a result, infiltration through the furrow sides can be substantial in comparison with the flow through the bottom. Such a flow process is two-dimensional and dependent on flow depth (and thus wetted perimeter), which varies as a function of distance and time. In WinSRFR, furrow infiltration computations are defined by: (a) selecting a method for modeling two-dimensional furrow infiltration effects, and (b) selecting an infiltration equation. Four options are available for the former, which are selected with the **Wetted Perimeter** control:

- **Furrow Spacing**
- **NRCS Wetted-Perimeter**
- **Representative Upstream Wetted-Perimeter**
- **Local Wetted-Perimeter** (Advanced user option)

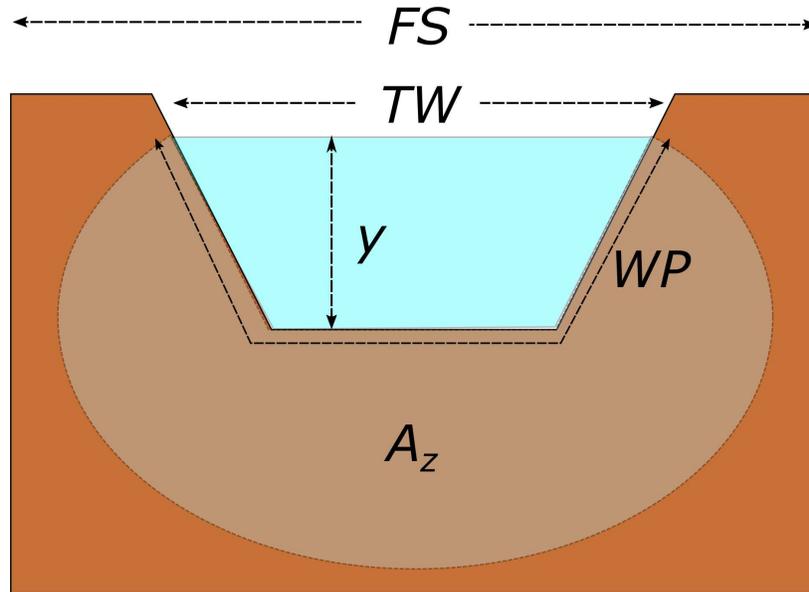


Figure 5.16: Infiltration in furrows

Modified Feature!

WinSRFR 5.1 makes three important changes to the implementation of furrow infiltration modeling options with respect to previous versions:

- Previously, an infiltration function was defined by selecting first an infiltration equation and then the wetted-perimeter option. In version 5.1, the wetted-perimeter option has to be selected first, as this is the interface assumed for two-dimensional furrow infiltration calculations. Available choice for the infiltration equation depend on this selection.
- The Local Wetted-Perimeter Option offers now an additional choice for the infiltration equation, the semi-physical Warrick-Green-Ampt equation.
- The interface through which macropore infiltration takes place is difficult to define. In the field, water can sometimes be observed flowing from one furrow to its neighbors, or can be observed flowing in cracks ahead of the apparent stream front. Clearly, this flow process does not depend on the wetted perimeter. In previous versions of the software, macropore infiltration was defined inconsistently, based on the selected Wetted Perimeter option. WinSRFR 5.1 defines it as a function of furrow spacing only, and thus strictly as a one-dimensional (in the vertical direction) flow process.

The key controls for configuring infiltration are the [Wetted-Perimeter](#) and [Infiltration Equation](#) drop-down selectors. Wetted-perimeter needs to be selected first and, thus, is displayed above the equation selector. The infiltration equations choices depend on the selected wetted

perimeter. Likewise, different parameter input boxes are displayed depending on the selected equation.

5.4.2.1 Wetted-perimeter options

Furrow spacing (Strelkoff and Souza, 1984):

$$A_z = z \cdot FS \quad (5.16)$$

This is the default method for representing furrow infiltration and is available in all WinSRFR Worlds. It is reasonable approach when the flow is very wide and shallow and the analysis considers a small range of inflow rates. In Eq. (5.16), FS is the furrow spacing and z is an infiltrated depth. Eqs. (5.7), (5.8), or (5.12) can be used in combination with Eq.(5.16).

With this option, it is important to be aware that a given z function cannot be used in combination with arbitrary values of FS . This is because Eq.(5.16) is a computational artifact used to adapt a particular infiltration modeling approach to the WinSRFR user interface. That approach, used in various furrow irrigation models, assumes that wetted perimeter effects are the same for any inflow and, consequently, that furrow infiltration is a function of opportunity time only. With that assumption, and if using the Modified Kostiakov equation, A_z is expressed as

$$A_z = K\tau^a + B\tau + C \quad (5.17)$$

The dimensions of the upper-case parameters K , B , and C are $[L^2 / T^a]$, $[L^2/T]$ and $[L^2]$, respectively (volume per unit length). If an infiltration function is specified as in Eq. (5.17), then a z function compatible with WinSRFR is determined by dividing the parameters of Eq. (5.17) by FS . Clearly, two-dimensional infiltration effects are embedded in the upper-case parameters of (5.17), and not in those of the resulting z function. Furthermore, z does not represent a one-dimensional infiltration function.

It follows from the above that the parameters of the function z need to be adjusted whenever the furrow spacing is adjusted, for example, if FS is doubled, then the parameters k , b , and c need to halved. This will produce the same A_z values as the original function (5.17) for any opportunity time. When using the Event Analysis World to estimate an infiltration function with the furrow spacing option, the application reports the parameters of the z function for the specified FS . If an infiltration function is derived with different software or from published results and is in the form of Eq.(5.17), then the parameter conversion has be conducted manually by the user. The same limitations and conversion procedures apply when modeling A_z with the Kostiakov or Branch infiltration equations.

NRCS empirical wetted perimeter (USDA-SCS, 1984):

$$A_z = z_{IF} \cdot WP_{IF} \quad (5.18)$$

This option is available with all User Levels and in all Worlds. The NRCS infiltration families were originally developed for border/basin irrigation (with dimensions of volume/area). They were adapted to furrow irrigation by assuming that total infiltration varies linearly with an empirical wetted perimeter WP_{NRCS} , defined based on flow conditions at the inlet (USDA-SCS, 1984; Walker et al., 2006). z is an infiltration depth calculated with the previously defined NRCS infiltration families. Hence, the NRCS method represents the furrow infiltration process as a quasi-one-dimensional flow problem, with water infiltrating normal to the surface, independent of the geometry.

In the NRCS method, infiltration varies with inflow through its effect on wetted-perimeter. WP_{NRCS} has two components, which are handled by the software:

$$WP_{IF} = WP_g(Q_0, n, S_0) + \Delta WP \quad (5.19)$$

WP_g is an approximation to the geometric wetted perimeter at the inlet, dependent on inflow rate, bottom slope, and hydraulic resistance, represented by the Manning roughness. ΔWP is a constant wetted perimeter increment (0.213 m = 0.7 ft), used to account for lateral infiltration, in addition to the infiltration that occurs in the direction normal to the infiltrating surface (USDA-SCS, 1984; Walker et al., 2006). This implies, therefore, that lateral infiltration increases as a function of τ^a . Appendix C.3 discusses the limitations of this approach.

Representative Upstream Wetted Perimeter (Strelkoff, 1990; Bautista, 2016):

$$A_z = z \cdot WP_{us} + c \cdot FS \quad (5.20)$$

This method is available with all User Levels and in all Worlds. Like the NRCS method, it adjusts total infiltration based on the wetted perimeter at the inlet (WP_{us}) under the assumption of a quasi-one dimensional flow process. It differs from the NRCS approach in that:

- Equation 5.20 can be used in combination with equations 5.7, 5.8, and 5.12. With any of these selections, infiltration volume per unit area through the soil matrix (z) is calculated as $z = k\tau^a$ or $z = k\tau^a + b\tau$. Macropore infiltration is represented with the c term of Eqs.(5.8) or (5.12).
- Lateral infiltration effects are built into the user-calibrated parameters of z .
- WP_{US} , is calculated from the given furrow geometry (trapezoidal or parabolic), the average inflow rate, and an estimate of the friction slope instead of the field bottom slope:

$$WP_{US} = f(fg_1, fg_2, Q_0, n, S_f) \quad (5.21)$$

In the above expression, fg_1 and fg_2 represent furrow geometric parameters. The resulting upstream wetted perimeter is close to the value predicted with unsteady flow simulation for any non-zero (downhill) slope value.

Local wetted-perimeter (Advanced User Level only):

$$A_z = z(y(x, t)) + FS \cdot c \tag{5.22}$$

With this option, infiltration through the soil matrix is calculated as a function of a one-dimensional infiltration function z and the local flow depth hydrograph $y(x, t)$. Infiltration through macropores is calculated as a function of furrow spacing, as has been previously explained. Two choices are available for representing, one empirical (used in combination with equations 5.8), and the second semi-physical, identified here as the Warrick-Green-Ampt (WGA) equation, which is described below. The Local Wetted Perimeter option is available for Simulation and Event Analyses only.

When combining Eq. (5.22) with Eq.(5.8), total infiltration at a flow cross section is the sum of infiltration through different wetted-perimeter increments, each with its own opportunity time. When Eq. (5.22) is combined with the WGA model, described below, the flow depth hydrograph affects both the wetted-perimeter and the water pressure acting at that location.

5.4.2.2 Furrow infiltration equations

Table 5.1: Wetted-perimeter and infiltration equation combinations used by WinSRFR

Wetted perimeter option	Infiltration equations
<ul style="list-style-type: none"> • Furrow spacing 	<ul style="list-style-type: none"> • Kostiakov • Characteristic infiltration time • Modified Kostiakov • Branch
<ul style="list-style-type: none"> • NRCS 	<ul style="list-style-type: none"> • NRCS infiltration families
<ul style="list-style-type: none"> • Representative upstream wetted perimeter 	<ul style="list-style-type: none"> • Kostiakov • Modified Kostiakov • Branch
<ul style="list-style-type: none"> • Local wetted perimeter 	<ul style="list-style-type: none"> • Modified Kostiakov • Warrick-Green-Ampt

Table 5.1 summarizes the infiltration equations that can be used in combination with each of the wetted-perimeter options provided by WinSRFR. Except for the Warrick-Green-Ampt, which is discussed next, all other equations have been previously described. Note that empirical z functions (an equation in combination with a set of parameters) cannot be used interchangeably with different wetted-perimeter options. For example, if a z function is defined with the Representative Upstream Wetted-Perimeter option, then a different function has to be defined for those field conditions for either the the Furrow Spacing or Local Wetted-Perimeter options. The software provides a mechanism for making those conversions, which will be explained in Section 5.4.3.

Warrick-Green-Ampt equation (Warrick et al., 2007; Bautista et al., 2016b; Bautista, 2016)

$$A_z = z \cdot WP + \frac{\gamma S_o^2 t}{(\theta_s - \theta_0)} \quad (5.23)$$

This option is an approximate solution to the two-dimensional Richards equation. The first component on the right-hand side is the product of a one-dimensional infiltration process z that occurs normal to the wetted perimeter. The second component represents the lateral flow and is a linear function of time, the soil sorptivity S_o [L/T^{0.5}], and the soil water deficit. γ is a dimensionless parameter that adjusts the results closer to those computed with the 2-D Richards equation. It depends mostly on soil texture, but is also affected by initial and boundary conditions. Current studies suggest that its value ranges from 0.85 to 1, with lower recommended for heavier soils and larger ones for lighter soils.

Equation (5.23) was developed assuming a constant flow depth. A modified form of that expression is used by the software to account for the time-variable flow depth (Bautista et al., 2016b). Since z in Eq. (5.23) is calculated with Eq. (5.14), it is identified in WinSRFR as the Warrick-Green-Ampt (WGA) model. The parameters required by this equation are then the same as those required by Eq. (5.14), except for γ . Soil sorptivity is calculated from the Green-Ampt parameters. As indicated above, previous studies have suggested a range of values for γ . Those results were generated with z computed with the one-dimensional Richards equation. Clearly, γ will differ if z given by the Green-Ampt equation. For most practical problems, the parameters of Eq. (5.23) will be calibrated from field data and γ will be embedded with those parameters. Under those conditions, γ can be assumed to be unity.

5.4.3 Conversion of infiltration functions

Modified Feature!

Conversion of infiltration function to an alternative form is needed when the selected analytical procedure does not support the infiltration equation available to the user. For example, Design and Operations Analysis currently cannot be used in combination with either flow depth-dependent infiltration equations or with the Branch function. Conversions are also necessary with furrows when the user needs to use a particular wetted-perimeter modeling approach for the analysis (e.g, representative upstream wetted-perimeter), but the available infiltration function uses a different assumption (e.g., furrow spacing). Previous versions of WinSRFR made some conversions automatically, often without notifying the user. No mechanism was provided for making furrow infiltration conversions accounting for the wetted-perimeter effect. Given these limitations, WinSRFR 5.1 offers a new **Infiltration Function Editor** (Fig. 5.17). The Editor is accessed by pressing the corresponding button displayed in the lower-left corner of the Infiltration pane.

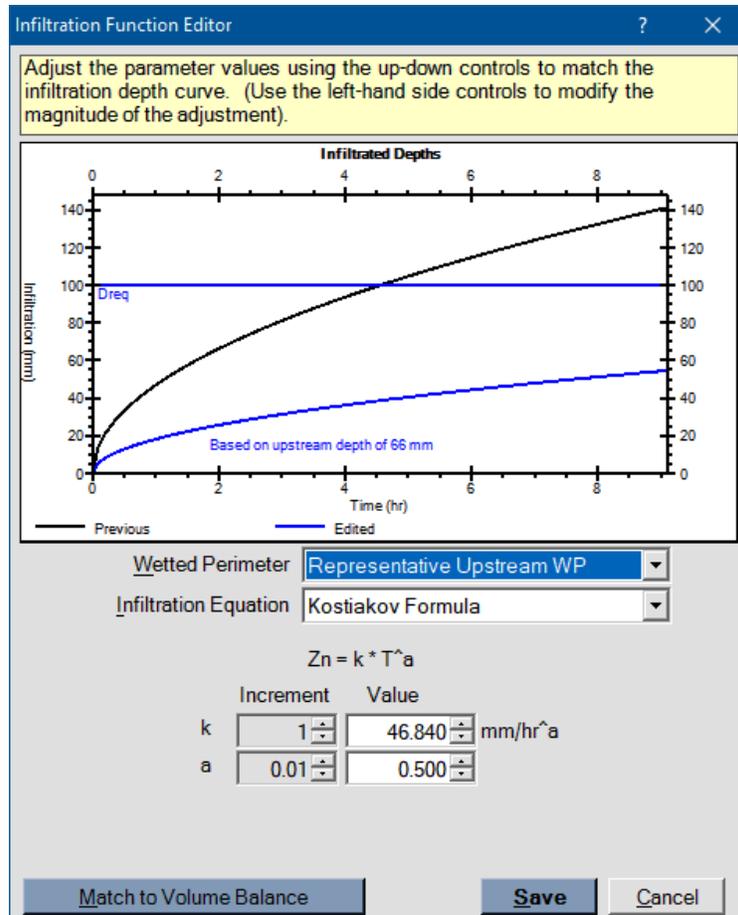


Figure 5.17: The Infiltration Function Editor

A conversion is carried out by, first, entering the original function in the Soil/Crop Properties tab. The editor is launched next. The controls displayed by the editor are essentially the same as those displayed in the Soil/Crop properties tab. The Editor allows the user to modify the parameter values with an up-down control according to user-specified increments. The example illustrated in Fig. 5.17 assumes that a furrow infiltration function was originally defined using the Furrow Spacing option and the Kostiakov equation. The conversion aims to develop a function compatible with the Representative Upstream Wetted Perimeter option, while continuing to compute z with the Kostiakov equation. The conversion requires, therefore, selecting the Representative Upstream Wetted Perimeter option, as shown in the figure, and determining a new set of Kostiakov parameters. The editor displays the original (Previous) and new (Edited) infiltration functions. Initially, the functions will not match because the Edited function is calculated using default values for k and a , provided by the Soil/Crop Properties tab. A new set of parameters can be found manually or automatically, in the latter case by pressing the **Match Function** button. Pressing the **Save** button replaces the original function with the converted one in the Soil/Crop Properties Tab, while the **Cancel** button preserves the original function.

In the example, a converted function that matches the original one for all times can be easily found by modifying only the constant k . In many cases, conversions will be approximate. In such cases, the conversions should aim to approximate the original function for opportunity times less than the time required to infiltrate $Dreq$, which is displayed in the editor. This is the criterion used by the Match Function tool. A sounder approach is to make the conversion for the range of infiltrated depths used to determine the original function. Otherwise, the conversion will incorporate extrapolated data. If the average infiltrated depth from the original evaluation is known, then $Dreq$ can be set to that value while making the conversion, and later reset to the value required by the new analysis.

If we assume that wetted-perimeter affects furrow infiltration, then those conversions need to account for the wetted-perimeter under which the original function was evaluated (see Section 6.3.1.2). When defining the original function, pertinent hydraulic conditions - cross-section, bottom slope, inflow rate, and/or hydraulic roughness - need to be set equal to those used in its determination. After completing the conversion, those hydraulic conditions can be reset to the values desired for subsequent analyses.

An added complication with furrow infiltration functions is converting from functions calculated with the furrow spacing, NRCS, or upstream wetted-perimeter option to functions that use the local-wetted perimeter option. The difficulty stems from the latter's dependency on flow depth as a function of space and time. Whenever possible, the EVALUE component of the Evaluation World should be used to derive flow-depth dependent infiltration functions. If a conversion to a flow-depth dependent form is needed, then the Infiltration Function Editor can be used to derive an initial approximate function, subject to the limitations described in the previous paragraph. The parameters can then be refined by and trial-and-error with the aid of simulation. The adjustment should aim to replicate as closely as possible the surface flow computed with the original function (flow depth and flow rate hydrographs, and thus the advance and recession trajectories). If this condition is satisfied, the converted infiltration function will predict the same or nearly the same final volume balance, and thus nearly the same final infiltration volume, as with the original infiltration function (Bautista, 2016). The final infiltration profiles will likely differ, however. Those differences provide a measure of wetted perimeter effects on infiltration for the particular field, and the importance of accounting for those effects.

5.4.4 Other options

The **Infiltration** pane displays three additional controls, the **Tabulated** and **Limiting Depth** checkboxes and the **Infiltration Table**, shown in Fig. 5.18.

Tabulated: The **Tabulated** check box control is used to specify spatial variations in infiltration properties. When this box is checked, the program displays a tabular data control.

Infiltration table: This table is used to specify infiltration parameters as a function of distance. When first launched, this control will display infiltration conditions at the

5.5.1 Standard inflow options

5.5.1.1 Inflow Method

Two options for entering inflow information are available to Standard Users. Those options are selectable from the Inflow Method drop-down list.

Tabulated Inflow: This Standard option allows the user to enter a table of measured time vs. discharge values, $Q_{in}(t)$ using the **Inflow Table** control. This option is available in the Event Analysis and Simulation Worlds, but not for Physical Design or Operational Analysis. As with other tabular data, hydrographs can be entered manually, by importing a text file, or from a spreadsheet using copy/paste. Menu commands available for entering hydrograph data are also similar to those available for other tabular inputs. The tab sheet generates a plot of the hydrograph, as a check on the input data. Procedures that use the tabulated inflow hydrograph assume a linear variation in flow rate with time in between measured values. Cutoff time needs to be specified for Simulation and Post-Irrigation Volume Balance Analysis (Merriam-Keller method). With tabular inflow data, this is done by inserting a zero flow rate value at the end of the table. The software interprets a non-zero flow rate value at the end of the table as an incomplete hydrograph. Two-Point Method Analyses can be executed with an incomplete hydrograph, as will be explained in section 6.3.

Standard Hydrograph: This option is used to specify, nominally, a constant inflow rate Q_{in} and a prescribed cutoff time t_{co} . When selected, WinSRFR displays an input box for these two variables. These nominal values can be adjusted using the controls in the **Cutoff Options** and **Cutback Options** panes. These controls allow simulation events to determine how inflow rate varies, instead of being prescribed as a function of time.

5.5.1.2 Cutoff options

The **Cutoff Options** drop down list is used to specify the time when inflow will be shut off. It is displayed only when the Inflow Method is a Standard Hydrograph. Input controls displayed by the form will vary depending on the option selected from this list. Those controls are denoted in the following paragraphs using the notation of this Manual.

Time-based cutoff: Cutoff occurs at the user-specified Cutoff Time T_{co} , the time elapsed since the start of the irrigation. This is the default selection when using a Standard Hydrograph. Inflow rate may vary, however, depending on cutback options described below. This is the only cutoff option offered for Event Analysis, Operations Analysis, and Physical Design.

Distance-based cutoff: Cutoff occurs at the advance distance $X_{co} = R * L$, where R is the Cutoff Location (a fractional value < 1.0) and L the field length given in the System Geometry Tab. This option, together with three Advanced User level options (described later), is offered for Simulation only.

NOTE

Use the distance-based cutoff option carefully (see also advanced user options)! If the flow is too small for the stream to reach the cutoff point, cutoff will not trigger. The application limits the number of time steps used during a simulation (1000), after which the user will have to choose to either continue or end the simulation. Choose the latter if the stream is advancing slowly.

5.5.1.3 Cutback options

The **Cutback Options** drop down list is used to model cutback irrigation. It is displayed only when the Inflow Method is a Standard Hydrograph. Input controls vary depending on the selection.

No Cutback: This is the default selection for the Standard Hydrograph.

Time-Based Cutback: Inflow rate is reduced at the specified Cutback Time and to the Cutback Rate Q_{cb} , expressed as a fraction of the initial Q ($Q_{cb} = RQ * Q$)

Distance-Based Cutback: Inflow rate is reduced to the specified Cutback Rate when the advancing stream reaches the specified Cutback Location.

The software will issue warnings when selecting invalid cutoff-cutback combinations. Still, cutback options need to be used cautiously as the specified cutoff may prevent cutback from triggering. For example, distance-based cutback may fail to take effect if cutoff prevents the flow to reach the cutback point.

Distance-based cutback should not be used with furrow systems if infiltration is computed with the NRCS or Representative Upstream Wetted-Perimeter options. The reason is that the average inflow rate needed to compute wetted-perimeter can only be determined after the simulation ends. In its place, the simulation engine uses the initial inflow rate, and therefore overestimates infiltration.

In the Design and Operations Worlds, no cutback is allowed for borders/basins, and only time-based cutback is allowed for furrows.

5.5.2 Advanced inflow options

Advanced boundary conditions include three additional options for specifying cutoff, and options for modeling surge and drainback irrigation systems. They are available for simulation only.

5.5.2.1 Cutoff options

Distance and Infiltration Depth: Cutoff occurs when a desired Infiltration Depth z , expressed as a fraction of D_{req} ($z = Rz * D_{req}$) has accumulated at a prescribed downstream Cutoff Location ($X_{co} = R * L$). Note that infiltration will ultimately exceed

the given infiltration depth, depending on the time needed for water to recede at the prescribed location.

Distance and Opportunity Time: Cutoff occurs when a given infiltration Opportunity Time (total elapsed time minus the advance time) has been experienced at a given downstream Cutoff Location ($X_{co} = R * L$).

Upstream Infiltrated Depth: In the case of furrows and basins, cutoff occurs when the infiltrated depth at the head end of the field matches the prescribed infiltration depth, expressed as a function of Dreq ($z = Rz * Dreq$). Ultimate infiltration will exceed the prescribed depth, depending on the lag time between cutoff and initial recession. In the case of graded border strips, WinSRFR attempts to calculate a cutoff time that will ultimately infiltrate the prescribed depth at the head end of the field. The algorithm relies on a dimensionless database of previously run simulations to predict the lag time necessary to achieve this objective.

5.5.2.2 Surge irrigation

This option is available for Simulation only. In surge irrigation, water is applied in pulses (on-off cycles). The following inputs are required to define a surge simulation problem:

Surge strategy: The Surge Strategy defines the duration of the on-off cycles. Four strategies are available. Additional input controls are displayed, depending on this selection.

Uniform Time: Surges take place at constant on/off time intervals. The Off-Time is assumed equal to the On-Time, defined in the **Surge On-Time** input box. The number of surges is calculated from the cutoff time. This option produces equal on-off times on both sides of the surge valve.

Uniform Location: With this option, during the advance phase, the on-time for a surge depends on the time needed for water to advance to a prescribed location. The advance increments are uniform. The off-time is equal to the on-time for the left-side of the surge valve, but equal to the on-time of the next advance surge for the right-hand side of the valve. The constant advance increment is calculated by dividing the field length by the **Number of Surges**. Thus, if field length is 100 m and 4 surges are requested, the program will calculate surges to 25, 50, 75 and 100m. After advance is complete, surging continues with Uniform Surge-On Time, and off-time equal to the on-time.

Tabulated Time: Surge by Uniform Location presents the practical challenge of detecting the advance front. A practical alternative is to use on-times of increasing duration in an effort to produce nearly constant advance distances. This is the surge strategy used in commercial surge valves. The **Tabulated Surge Times** table is used to define the increasing on-time surges. This table is also used to enter the uniform on-off times for post-advance.

Tabulated Location: This option works much like the Uniform Location option, except that the advance increments can be defined arbitrarily. The **Tabulated Surge**

Locations table is used to define the fractional surge distances. As with the Uniform Location option, a Uniform Surge On-Time is entered for the post-advance phase.

Practical surge irrigation systems use a surge valve to switch the water flow from one irrigation set, located on one side of the valve, to a second set located on the other side. This has the effect of turning the water on and off for each set. The on-time for each set is the same, but the off-time is different except when the on-time is constant and equal to the off-time (Uniform Time surge strategy). As a result, irrigation performance may change slightly from the first to the second set. If the performance of the second set needs to be examined, then conduct an analysis for the first set with the Tabulated Time, Uniform Distance, or Tabulated Distance surge strategies, and use the output to define a surge problem for the second set, using the Tabulated Time strategy.

Inflow Rate: This value is entered in the corresponding input box. Inflow rate is assumed constant during each surge.

Cutoff Time: Time at which inflow stops. Cutoff time overrides the defined surge strategy. Hence, if cutoff time is reached in the middle of a surge, the surge will be terminated. Cutoff time does not need to be specified (i.e., the **Cutoff Time** input box is not displayed) when the Surge Strategy is Tabulated Time, because the end time for the last surge is assumed to be the cutoff time.

Surge infiltration method: WinSRFR offers two empirical choices for modeling the effect of surge on infiltration, selected with option buttons. The effect of surge on infiltration is still not well understood and, thus, results need to be interpreted carefully.

Blair-Smerdon: This option assumes that the infiltration rate will continue to decrease during the off-time, just as if water was flowing continuously (Blair and Smerdon, 1987). Hence, the opportunity time at any point is a function of the total time. This option works with any infiltration formulation.

Izuno-Podmore: With this option, the infiltration rate during the second and subsequent surges is set to the steady infiltration rate (Izuno and Podmore, 1985; Izuno et al., 1985). This option will work only with the Modified-Kostiakov and Branch functions. In both cases, the steady infiltration rate term b must be non-zero.

5.5.2.3 Drainback irrigation

Modified Feature!

This option is being revised and is currently disabled.

Drainback irrigation is a Simulation World option. With these systems, the surface volume is allowed to drain back into the supply channel after cutoff. The resulting runoff increases the inflow available to the next basin to be irrigated. These systems typically have a blocked

downstream end and zero or slightly adverse slope.

The rate at which water drains off the field depends on the water-surface elevation in the supply channel. Thus, drainback calculations change the upstream boundary condition from a specified inflow rate to a specified upstream flow depth. Initially, the upstream flow depth is assumed equal to the flow depth calculated by the program (the water surface elevation in the supply channel is equal to the water surface elevation at the field inlet). The software assumes that the water level in the supply channel decreases linearly with time. Eventually, the water level in the channel matches the field invert. At that point the boundary condition is zero flow depth and outflow stops. The required inputs are:

Drainback. This check box enables drainback calculations.

Draw-Down Time. The time needed for the supply water level to drop to the field invert. This value needs to be measured in the field, as it depends on the characteristics of the supply channel.

The drainback option, as currently implemented, only simulates the first basin in a drainback system. Other basins (except the last) can be modeled by adding the drainback outflow to the inflow rate from the supply channel. The last basin in a system receives this combined flow as well, but cannot drain back into the supply channel. Thus, drainback has to be turned off when simulating the last basin in a drainback system.

5.5.3 Downstream condition

Use the [Downstream Condition](#) option buttons to indicate if the system has an open or blocked downstream end. Runoff will be produced in the former case if the stream reaches the field end. This is the only input that needs to be provided for Simulation, Operations, and Physical Design analyses.

Event Analysis procedures require a measured outflow hydrograph if the system is free-draining systems. Those data are used to calculate runoff volume and, ultimately, volume balance. Runoff is specified with the controls displayed in the Runoff pane.

The [Downstream Condition](#) option buttons and [Field Measurements](#) checkboxes replicate the controls in the Start page and are provided for convenience. The runoff hydrograph, flow rate as a function of time, is specified with the [Runoff Table](#). The initial runoff time must coincide with the advance time to the end of the field reported in the Advance Time table. The application linearly interpolates the outflow rate at times between the observed values, as required. If runoff was measured until all outflow ceased, then the [Partial Hydrograph](#) checkbox (located below the table) should remain unchecked and the last entry in the [Runoff Table](#) should show a zero flow rate value. Otherwise, check [Partial Hydrograph](#). Chapter 7 explains how the runoff data must be specified for different types of event analyses.

HYDRAULIC SIMULATION

Chapter 5 discussed the variables used to describe the irrigation system (geometry, infiltration, roughness, and boundary conditions), and the options available for specifying those properties. All options are available for setting up hydraulic simulations but only a subset can be used with Event, Operations, or Design Analyses. This chapter discusses additional inputs available for setting up hydraulic simulations and the simulator outputs. Advanced simulation features, namely the Fertigation option and setting up simulations with the Richards infiltration equation, are discussed in Chapter XX.

6.1 Inputs

In addition to the Common Input tabs, the following tabs are displayed by the Simulation World:

Data Summary Tab: The **Data Summary** tab (Fig.6.1) summarizes inputs from the System Geometry, Soil/Crop Properties and Inflow Management tabs. The Data Summary tab page can be used to edit input values but not input options. For example, the tab page can be used to edit the parameters of the selected infiltration equation, but not to select an alternate equation. The Data Summary tab cannot be used either for editing tabular data.

Execution tab: A simulation is run by pressing the **Run Simulation** button in the Execution Tab (Fig. 6.2) or by pressing CTRL-R. The following options can be modified prior to execution: (a) **Solution Model**; (b) **Cell Density**; and (c) **Graphics Output Options**.

Solution Model: Two solution models are used by WinSRFR:

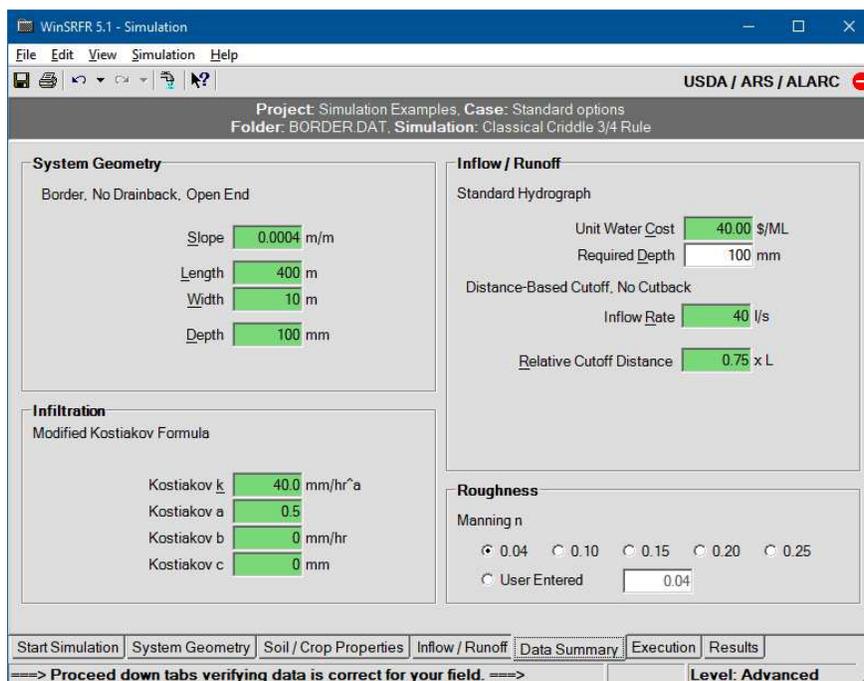


Figure 6.1: Simulation: Data Summary tab

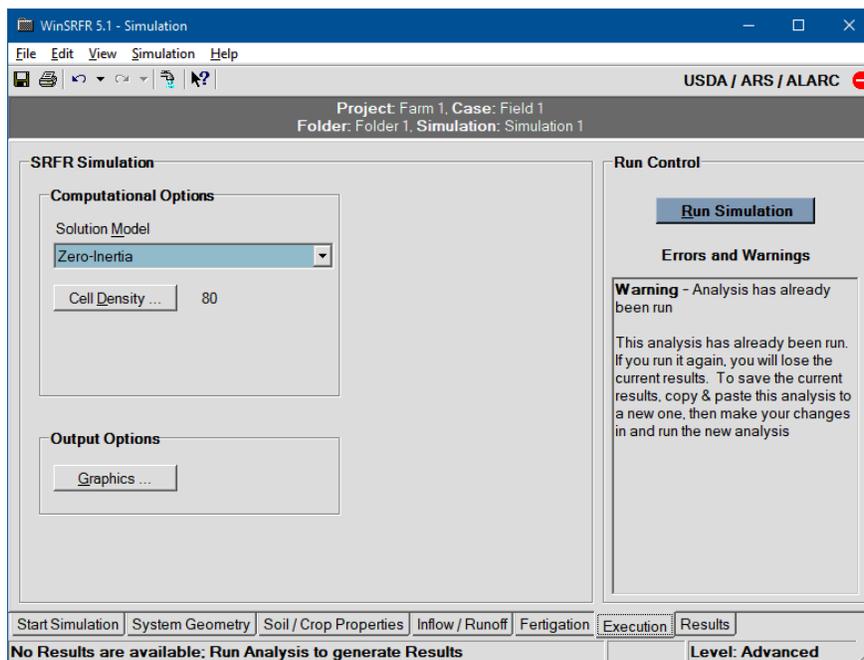


Figure 6.2: Simulation: Execution tab

- Zero-Inertia, and
- Kinematic-Wave.

For most simulations, users will not have to select the solution model. The application selects the zero inertia model if the field bottom slope is smaller than 0.004 [L/L]. It will also use the zero-inertia model for steeper slopes if the downstream end is closed. With a steep bottom slope and an open downstream end, the simulator will use the kinematic wave model. An Advanced user can override these selections except when the downstream boundary is closed. In that case, the only choice is zero-inertia. The simulation engine will issue a warning if selecting a model that is not recommended for the given data.

Since the Event Analysis, Design, and Operation Analysis Worlds use the SRFR engine to support their calculations, the Solution Model is selectable also in those Worlds.

Cell Density: The solution scheme used by SRFR divides the stream into discrete spatial increments. Cell density determines the number of spatial increments and, therefore, the size of computational cells. This option is mostly a legacy of older numerical schemes in which the user defined the computational grid to ensure numerical accuracy. The simulation engine has built-in logic that adapts the spatial and temporal discretization depending on the particular flow conditions. As a result, most simulations will produce spatial cell densities different from the nominal cell density (shown to the right of the Cell Density button). For most practical problems, the cell density recommended by the program will generate numerically accurate results. Still, a good practice is to repeat the simulation with a higher cell density, to verify the results of the original simulation. Pressing the Cell Density button will bring up the Simulation Density Dialog box (Fig. 6.3). A larger cell density should always be tested when a simulation produces

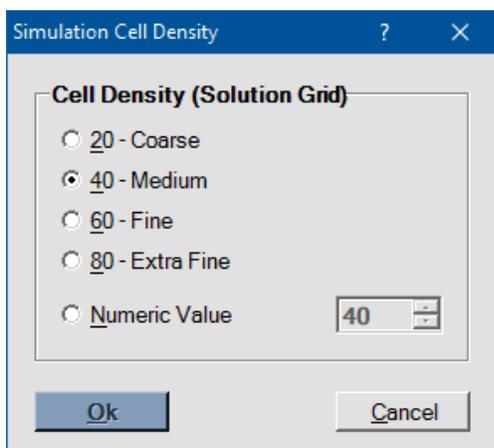


Figure 6.3: The Simulation Cell Density dialog box.

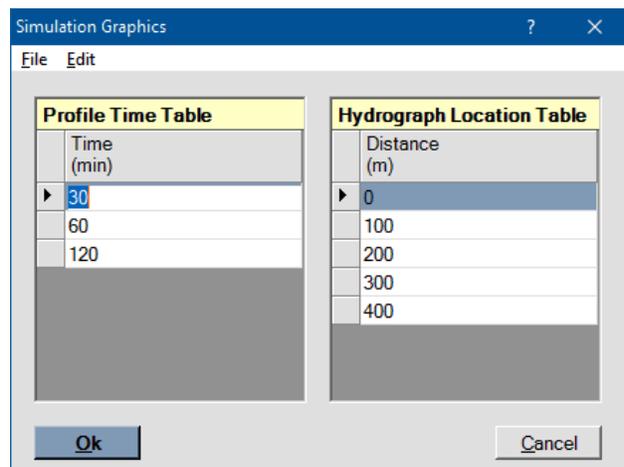


Figure 6.4: The Simulation Graphics dialog box.

a large volume balance error. The volume balance error (Verr%) is reported in the Summary output tab, and typically is less than 1%. At the same time, cell density should not be increased arbitrarily because it increases the execution time, eventually with little gain (or even loss) in accuracy.

Graphics: As part of the simulation output, the application plots a set of depth hydrographs and flow depth/water surface elevation profiles. By default, the application plots the hydrographs at five equally spaced locations, including the field boundaries, and the profiles at three times. The number of displayed graphs can be edited with the Graphics button. Pressing this button will display the **Simulation Graphics** Dialog Box. The dialog box has two editable tables (Fig.6.4):

- The **Profile Time Table** specifies the times at which WinSRFR captures and displays surface profile data.
- The **Hydrograph Location Table** specifies the locations at which WinSRFR captures and displays flow rate/depth hydrograph data.

NOTE

The Hydrograph Location Table expects the field length to be given in the last row of data. If the table contains any other value, the program will set the hydrograph locations to default values.

6.2 Outputs

The set of tabular and graphical outputs generated by a simulation are summarized in Table 6.1. Graphical outputs can be copied and pasted to other Windows applications, or can be exported to file in a variety of formats. The underlying data for the graphical outputs can also be copied and pasted to other applications that accept tab-separated text. Examples of the Hydraulic Summary and Infiltration Function graphical outputs are depicted in Fig. 6.5.

Modified Feature!

The Infiltration Function graph, identified as Upstream Infiltration in Version 4.1, now has a double vertical scale. The left-hand side scale presents results as volume/length, and the right-hand scale as depth.

A particularly important output is the volume balance error reported in the Summary tab page, Verr%. This error is computed by comparing the inflow volume with the sum of the infiltrated and runoff volumes (the latter, with free-draining systems). This error generally is close to zero, and in general, should be no greater than 1%. Extremely large errors are indication of computational incidents that are not handled adequately by the simulator.

Table 6.1: Simulation outputs.

Tab page	Description
Summary	Summary of inputs and computed performance indicators. The notation used in the Summary page is defined in Section 1.10.3.
Hydraulic Summary	Combined graph displaying the inflow/outflow hydrographs, advance/recession trajectories, and the final infiltration profile.
Advance /Recession	Advance and recession as a function of time. The Advance tab displays advance data alone.
Infiltration	Depth of infiltrated water as a function of distance. The infiltration (Ordered) tab arranges these values in descending order
Infiltration Function	Plot of infiltration volume per unit length as a function of time, computed from the simulation results. The plot also displays on the right-hand side axis a scale that converts the function to depths. For borders/basins, infiltrated depth is calculated as the infiltrated volume per unit length divided by the border width. For furrows, it is calculated as the infiltrated volume per unit length divided by furrow spacing.
Hydrographs (Flow & Depths)	Flow rate/depth as a function of time at specified hydrograph locations
(Depth/Elevation) Profiles	Water surface depth/elevations as a function of distance computed at the times specified in the Profile Times table.

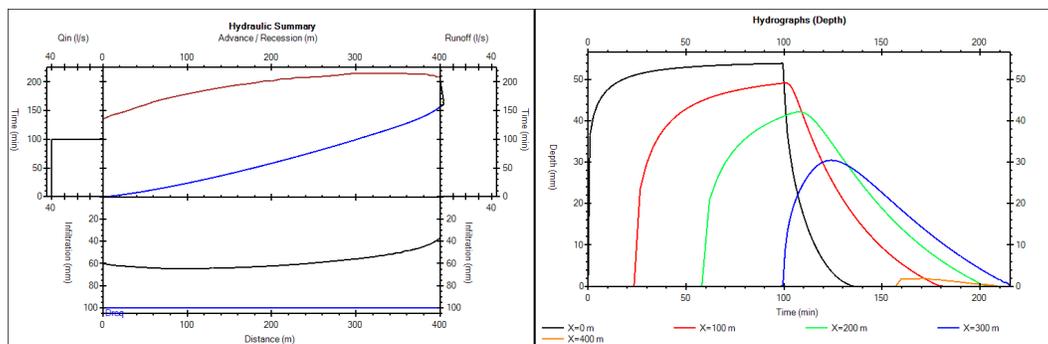


Figure 6.5: Simulation graphical outputs: hydraulic summary and flow depth hydrographs.

6.2.1 The Simulation Animation Window

The results of a successful simulation can be viewed with the **Simulation Animation Window** (Fig. 6.6). This tool is enabled with the *Simulation/View Simulation Animation Window* menu item or as a user preference option (*Edit/User Preferences/Views/Show Simulation Animation*). Use the tool controls to replay the simulation and save the output. Individual frames can be saved (File/Save Frame as) in different graphical formats, while complete simulations can be saved (File/Save Animation as) as an animated GIF file.

By default, the Animation displays the time evolution of the surface flow profile in the upper part of the screen and the infiltrated profile in the lower part. The window can be configured to display other flow variables and to include a third graph. Controls are provided as well for adjusting the vertical and horizontal axes, to facilitate the inspection of results. The Simulation Animation Window is particularly useful for examining overflow conditions or computational anomalies.

The Animation Window displays data for the most recently executed simulation. Unlike the data displayed in the output tabs, those data will be erased from memory when a new simulation is run.

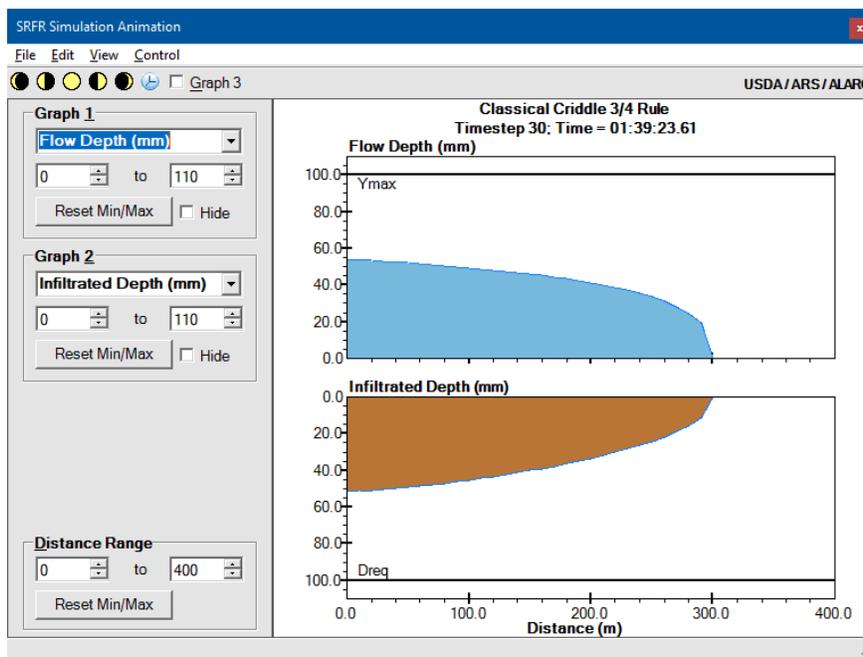


Figure 6.6: The Simulation Animation Window.

6.2.2 Simulation Network

This tool (Fig.6.7), available only for Advanced users, can be used to inspect the detail of hydraulic simulations. It is mainly a research tool, but can be used also to identify computational anomalies. The **Simulation Network** will be displayed by pressing the menu

command *Simulation/Simulation Network* or the shortcut F7.

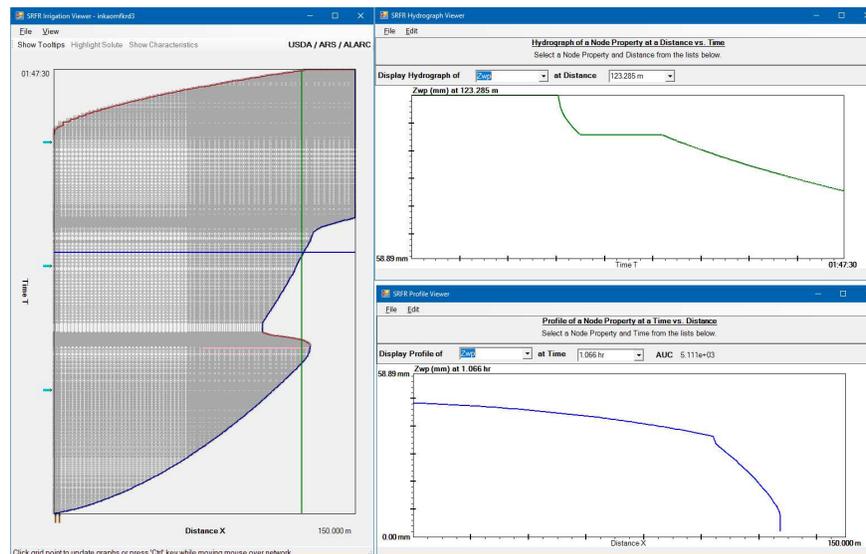


Figure 6.7: Simulation Network

The Simulation Network tool has three components. To the left is the **Irrigation Viewer**, which depicts the computational grid. To the right are the **Hydrograph** and **Profile Viewers**. The Hydrograph Viewer displays a user-selected hydrograph (a time series) at a selected location along the stream. In this example, the illustrated time series is z (infiltrated depth) at a distance of about 118 m. In contrast, the Profile Viewer shows a user-selected flow profile (a space series) at a selected simulation time. In the example, the space series is the infiltrated profile approximately 1 h after the start of the irrigation. The blue and green intersecting lines in the Irrigation Viewer identify the currently plotted time and space series. Locations and times for which flow data are available depend on the computational grid generated by the numerical solution. The selected location and time can be changed by clicking in the Irrigation Viewer or by using the right-most drop down control on the respective viewer. Pressing the CTRL key while navigating with the mouse over the Irrigation Viewer forces the hydrograph and profile viewers to update their display dynamically.

The variable to be displayed with the hydrograph or profile viewers can be changed by clicking on the left drop down-control (**Display Hydrograph Of ... /Display Profile Of ...**). Infiltration, flow depth, water surface elevation, and discharge are some of the variables that can be inspected. The example illustrated in Fig. 6.7 shows that with the given inflow hydrograph, advance stopped after some time and front-end recession ensued. The flow rate increased to the point where advance restarted and eventually reached the end of the field. Hence, the peculiar shape of the infiltration time series at the selected point.

The Irrigation Viewer has a View menu command. The *View/Inputs* command displays inputs to the simulation and is useful for diagnosing potential problems with the inputs. All inputs are shown in SI units. The *View/Animation Window* command is used to animate

user-selected results. The other two menu items are used to reopen the hydrograph and profile viewers, in case either one is closed.

Like the Animation Window, the Simulation Network can only display the results of the most recent simulation, i.e., data that is still in memory. Although the detailed data is not saved in the *.srfr file, both viewers allow the user to copy/export the graphical results or the underlying data (use the Edit menu or right click on the viewer to bring up a context menu). Thus, detailed simulation results can be saved to a text or spreadsheet file.

6.3 Examples

Before running any of the example files, create a working copy in a folder different from the installation directory. See Section 1.4.2.

6.3.1 Infiltration

The scenarios in the *Infiltration Examples.srfr* file compare different infiltration modeling options. The project consists of three case folders, one dealing with one-dimensional border/basin irrigation, the second with two-dimensional furrow irrigation, while the third illustrates how two-dimensional infiltration eventually can be modeled as a one-dimensional flow process. Execute the scenarios in each case folder and contrast them using the Data Comparison tool. You will need to set the user level to Advanced to execute several of these scenarios.

6.3.1.1 Border

The *Free-draining border* simulation folder deals with a sloping, free-draining border system. The scenarios are identical except for the infiltration modeling approach. The empirical NRCS infiltration families and Modified Kostiakov equation, and the semi-physical Green-Ampt equation were used in this comparison. A reference scenario was defined with the NRCS 0.5 family. The Modified Kostiakov and Green-Ampt equations were parameterized to replicate as closely as possible the advance, recession, and runoff of the reference scenario. Since the Green-Ampt parameters have physical meaning, they were adjusted within realistic ranges of values.

Compare the advance and the recession trajectories with the Advance/Recession tab and the runoff hydrographs with the Inflow/Runoff tab and verify that, in fact, the Modified Kostiakov and Green-Ampt scenarios replicate the surface flow predicted with the NRCS scenario. Compare now the final infiltration profiles. The profiles computed with the NRCS and Modified Kostiakov equations are essentially the same. The profile in the Green-Ampt scenario is slightly rotated, with more infiltration upstream and less downstream. Since the Green-Ampt equation accounts for the effects of flow depth, this result reflects the variation in flow depths along the field, which are greater upstream than downstream. Finally, compare the upstream infiltration curves. The empirical infiltration functions differ slightly for

opportunity times less than 1 hour. Although they match for long times in the Upstream infiltration tab, it is easy to show that the functions deviate for times greater than shown in the graph. Hence, different equations can be used to represent the same infiltration process, but for only a limited time. The Green-Ampt function predicts more infiltration with time in comparison with the empirical functions. This is because the empirical functions represent an average function that applies everywhere along the field, while the Green-Ampt function is shown only as it applies at the upstream end of the field.

In typical irrigation studies, infiltration functions will be extrapolated to hydraulic conditions (and perhaps times) different from those used to develop them. The scenarios in the folder *Level Basin* examine the problem of extrapolating those functions to different hydraulic conditions.

The scenarios apply the infiltration functions of the preceding scenarios to the analysis of a short, level-basin system (blocked border with zero zlope). Compare first the upstream infiltration curves for the NRCS, Modified Kostikov, and Green-Ampt scenarios in the *Free-Draining Border* folder with the corresponding scenario in the *Level Basin* folder. Unlike the empirical functions, infiltration predicted with the Green-Ampt equation increases because of the larger inflow rate, and consequently, flow depths. Compare now the predicted advance, recession, and final infiltration profile of the scenarios in the *Level Basin* folder. Differences between the NRCS and Modified Kostikov scenarios are slight. While recession times are noticeably smaller and the infiltration profile less uniform with the Green-Ampt scenario, the performance indicators shown in the Indicators tab are for practical purposes nearly the same and would lead to similar operational recommendations. The reader is encouraged to test other hydraulic scenarios and verify that irrigation performance predictions are not very sensitive to the infiltration equation selected for the analysis when infiltration is one-dimensional.

6.3.1.2 Furrow

The *Sloping, free-draining furrow* case folder consists of two simulation folders. The scenarios contrast the four different methods used by the software to model wetted-perimeter effects. Scenarios in each folder have the same length, cross-section, spacing, slope, resistance, and boundary conditions. Since most methods can be used in combination with more than one infiltration equation, the analysis was limited to the following combinations:

- NRCS empirical wetted-perimeter and NRCS infiltration families (NRCS)
- Furrow Spacing and Modified Kostikov (FS-MK)
- Representative Upstream Wetted-Perimeter and Modified-Kostikov (WP0-MK)
- Local Wetted-Perimeter and Warrick-Green-Ampt (LWP-WGA).

The label in parenthesis is used to identify each of the scenarios in the following paragraphs. A reference scenario was created with the NRCS 2.0 infiltration family. The FS-MK, WP0-MK, and LWP-WGA scenarios were parameterized to replicate the advance, recession, and

runoff of the NRCS scenario.

Examine first the scenarios in the *Wide Furrow* simulation folder. Independently of the infiltration equation used, infiltration calculations based on the NRCS, furrow spacing, and upstream wetted-perimeter methods only account for opportunity time as a function of distance. Therefore, different infiltration functions fitted to the same advance, recession, and runoff data, as assumed in these examples, will represent the same infiltration process. You can see this by inspecting the corresponding curves in the Upstream Infiltration and Final Infiltration tabs. As with one-dimensional infiltration cases, these different infiltration functions are equivalent for a limited time. The Warrick-Green-Ampt calculations incorporate the effect of time- and space-variable flow depth, and therefore, variable wetted-perimeter. Hence, the upstream infiltration curve displays greater infiltration amounts with time than with the empirical functions and the infiltration profile is less uniform.

The scenarios in the first folder considered a trapezoidal furrow cross-section with a 0.2 m bottom width, 1:1 side slope, and a 0.06 m maximum depth. The scenarios in the *Narrow furrow* folder consider a narrower (0.1 m) and deeper (0.075 m) furrow which causes flow depths to increase and wetted-perimeters to decrease (by nearly 20 %) for the given flow in comparison with the *Wide Furrow* example. Use the Simulation Network tool to view the wetted-perimeter values at the upstream end of the field.

Compare first the wide and narrow furrow scenarios generated with the NRCS infiltration family. The predicted advance, recession, runoff and final infiltration profile are nearly the same despite the change in wetted-perimeter. This is because the NRCS empirical wetted-perimeter used for infiltration calculations is a function of slope, inflow rate, and resistance, but not of the cross-sectional geometry. Hence, the same infiltration is being calculated in both cases even though the wetted-perimeter used for hydraulic computations (and flow depth) differs. Much larger differences in the cross-section are needed to produce visible differences in the surface flow. This highlights an important limitation of the NRCS method, which was designed for a narrow range of cross-sectional geometries. In addition, and even for typical shapes, the NRCS empirical wetted-perimeter formula severely over-predicts wetted-perimeter with small slopes.

Infiltration is independent of wetted-perimeter effects when using the Furrow Spacing option. As a result, and as with the NRCS scenarios, advance, recession, runoff, and final infiltration predictions are nearly identical despite differences in the computed flow depths.

The WP0-MK and LWP-WGA scenarios in the *Narrow furrow* folder predict less upstream infiltration than their wide counterparts. Therefore, advance is faster, runoff rates larger, less water infiltrates, and the final infiltration profiles are more uniform. The WP0-MK scenario produces the largest decrease in infiltration depth, and consequently, largest increase in runoff, while scenario LWP-WGA produces smaller changes. This difference is partly related to the fact that one method uses only a representative wetted-perimeter and the other accounts for its spatial and temporal variation. Another factor contributing is the second term in the WGA equation, which is essentially independent of wetted-perimeter.

Because of this component, infiltration predictions with the LWP-WGA equation are less sensitive to wetted-perimeter changes than with the WP0-MK equations.

Clearly, caution needs to be exercised when extrapolating furrow infiltration function to hydraulic conditions different than the ones used to develop them. This includes changes to the inflow rate, roughness coefficient, slope, and cross-sectional description. From soil physical principles, infiltration should increase with wetted-perimeter. Some field studies have verified this effect, but others have not. Infiltration variability and the formation of surface seals make two-dimensional infiltration effects difficult to measure. In addition, furrow infiltration becomes one-dimensional when the wetting bulb of neighboring furrows merge. This factor is ignored in the simulations. Given this uncertainty, the sensitivity of the predicted performance to different infiltration modeling approaches needs to be tested when developing design and operational recommendations. Any selected furrow infiltration modeling approach needs to be verified with field measurements under different hydraulic conditions.

6.3.1.3 1D vs 2D infiltration

The scenarios in the *1D vs 2D infiltration (Green-Ampt)* case folder show how two-dimensional infiltration becomes essentially one-dimensional as the channel width increases. The first two scenarios are identical (length, slope, hydraulic resistance, inflow rate, downstream boundary condition), except for the cross section - a border and furrow, respectively. The border width and furrow spacing are both 1 m. The furrow has a trapezoidal cross-section with a 0.1 m bottom width. Infiltration for the border is modeled with the Green-Ampt equation while the Warrick-Green-Ampt equation is used for the furrow. The Green-Ampt parameters are the same for both scenarios.

Because of the difference in cross section, more water infiltrates with the border than the furrow. Hence, water advances faster in the furrow and runoff rates are greater. The infiltrated depth for the furrow is slightly over 60% of the border case (see values in the Indicators tab), even though the wetted-perimeter is nearly 35% of the border width (displayed in the Simulation Network tool). The third scenario is a copy of the second one, but with a wider furrow bottom (0.7 m). The upstream infiltration curves for this scenario approximate that of the border. Hence, advance and runoff predictions are closer to each other while the predicted final infiltrated depths are the same even, with the furrow wetted-perimeter equal to about 80% of the border width. These results highlight the contribution of the second component of Eq. 5.23 which, as was noted before, is largely independent of wetted-perimeter. That contribution becomes relatively small as wetted-perimeter increases. This is shown with the last two scenarios, which consider a 3 m border and a furrow with a 3 m spacing and 2.9 m bottom width. The inflow was increased in proportion to the change in width. The upstream infiltration functions for the furrow and border flow are in close agreement, and consequently, the predicted surface and subsurface flow are very similar for these last two scenarios. Use other furrow and border dimensions to test the effect of a wider furrow.

6.3.2 Simulation Options

The *Simulation Options.srfr* file illustrates the use of several simulation configuration options. The file also aims to highlight capabilities and limitations of the simulation engine. The file contains five case folders.

6.3.2.1 Boundary Conditions

This case folder illustrates the use of different Boundary Condition configuration options. The scenarios are organized in four Simulation folders:

Cutoff Options: These scenarios demonstrate options for specifying distance-based cutoff, i.e., it forces the inflow to stop when the advancing stream reaches a specified distance from the field inlet. This is a practice often used by irrigators. Irrigators may also stop the inflow some time after water reaches the end of the field, hoping to satisfy the irrigation requirement or part of it at the expected point of minimum infiltration. These alternatives can be explored with cutoff based on distance, distance and infiltration depth, and distance and opportunity time. See Sections 5.5.1.2 and 5.5.2 for more details. The scenario Distance-based cutoff – incomplete advance illustrates a key problem with using distance-based cutoff in simulation. Cutoff is not triggered because the specified inflow-rate is too small relative to infiltration. The number of time steps used during a simulation then exceeds an internal limit set by the software. The simulation stops, issues a warning, and prompts the user to either continue or end the simulation. It is for this reason that distance-based cutoff should be avoided when running a batch job. Notice also that when specifying cutoff with distance and infiltrated depth or distance and opportunity time, cutoff does not occur exactly when that condition is satisfied, but some time later as determined by time-step of the numerical solution.

Cutback Options: Guidance for using the cutback options are provided in Section 5.5.1.3. Typically, cutback will be specified after the stream reaches the end of the field (Distance-based cutback) or based on the cutoff time (Time-based cutback). The scenarios in this folder compare irrigation without and with cutback in furrows. Results will vary depending on the wetted-perimeter option used to simulate furrow infiltration. If Furrow Spacing is selected, for the conditions of the example, final infiltration is the same with and without cutback. That is not the case when using the Representative Wetted-Perimeter Option. Infiltration will also decrease after cutback with the NRCS and Local Wetted-Perimeter options.

Variable Inflow: When the inflow rate is specified with tabular values, inflow rate will be assumed to vary linearly with time between the tabulated values. This is shown with the first scenario. The second scenario shows how to specify step inflow rate changes.

Surge Irrigation: The software offers four options for configuring surge irrigation, which are illustrated with this group of scenarios. See Section 5.5.2.2 for details on how to configure inflow for surge irrigation. The Uniform Times example applies equal and constant surge on/off times. With the Tabulated times example, surge on/off times follow a user-prescribed time schedule. In the Uniform Locations example, surge on/off

times are determined based on constant advance distance increments during the advance phase. Constant on-off times apply during the post-advance phase. Finally, with Tabulated locations, surge on-off times are determined from user-prescribed advanced distances. Constant on-off times apply for the post-advance phase.

6.3.2.2 Infiltration and Roughness

Variable Infiltration: The scenario in this simulation folder illustrates the use of a variable infiltration table. Note that infiltration properties are assumed to vary step-wise, as illustrated in the Infiltration Profile output tab, whether using an empirical infiltration equation, as in the example, or a semi-physical one.

Limiting Depth: The single scenario in this folder illustrates the use of the Limiting Depth checkbox. This option is useful when simulating the effects of a hardpan, case in which infiltration will cease after reaching the specified maximum value.

Hydraulic Resistance: The two scenarios in this folder compare modeling resistance with the Manning and Sayre-Albertson equations. The Sayre-Albertson χ was calibrated to replicate as closely as possible the advance, recession, and runoff predicted with a Manning n value of 0.04. The fitted χ value is reasonable considering values reported in the literature for furrows. There are some slight differences in the predicted recession times, and therefore, the declining portion of the runoff hydrograph. Examine also the depth hydrographs computed for each case (Hydrographs-Depths output tab). With the Sayre-Albertson equation, upstream depths are slightly smaller but downstream depths are slightly larger. These differences would be difficult to detect in the field.

6.3.2.3 Geometry

Variable Field Elevations: The scenarios contrast a simulation assuming a uniform zero slope with one assuming variable field elevations, but with an average zero-slope. Note that field elevations are assumed to vary linearly between tabulated values. As one would expect, efficiency and uniformity decline with a non-uniform field bottom in comparison with a uniform one. Be aware that variable elevations/slopes can cause computational anomalies.

Furrow Sets: With furrow irrigation, the specified inflow rate is divided by the value entered in the Number per Set control. The result is used to simulate a single furrow. Hence, flow rates displayed in various output forms (e.g., Hydrographs-Flow) represent values for single furrow. This is shown by contrasting the two scenarios in this folder.

Furrow Spacing 1: These scenarios illustrate the effect of furrow spacing on infiltration calculations when infiltration is calculated with the furrow spacing option. The Kostikov equation was chosen for the scenarios with a constant 46.84 mm/hr^a and an exponent of 0.5. The first two scenarios are identical except for the value of furrow spacing, 1 m and 0.76 m. View these scenarios with the Data Comparison tool. Even though the selected wetted-perimeter option, the infiltration equation, and the infiltration parameters are all the same, simulation results differ. This is because with this

infiltration option, the furrow spacing value is used to compute the infiltration function A_z as can be seen in the Infiltration Function tab (while the curves in the Infiltration Function A_z/FS are the same).

Execute now Scenario 3, in which furrow spacing is 0.76 m, but which uses a modified value of the Kostiakov constant, calculated as

$$k = k \times \frac{FS_1}{FS_2}$$

With this new value of k , the predicted advance, recession and runoff of Scenarios 1 and 3 match. Although the final distribution of infiltrated volume per unit length is the same (which is not displayed in the Data Comparison tool), the average infiltrated depth A_z/FS , shown in the Infiltration Profile tab, differs due to the difference in furrow spacing.

Furrow Spacing 2: These scenarios are similar to the ones in the previous folder except that they use the Upstream Wetted-Perimeter option to calculate infiltration, again in combination with the Kostiakov equation. The Kostiakov parameters are the same and, as in the previous folder, the scenarios consider furrow spacings of 1 m and 0.76 m. Since the infiltration function is independent of furrow spacing, both scenarios predict the same advance, recession, runoff, and final infiltration profile (A_z as a function of distance). The infiltration depth profiles (A_z/FS) differ due to the difference in furrow spacing.

6.3.2.4 Computational Features

These scenarios highlight capabilities of the simulation engine. Computational procedures used by the SRFR simulator depend partly on the inputs, and partly flow conditions generated by the simulation. The scenarios in this case folder describe some of these computational capabilities, while also highlighting some results that need to be interpreted carefully.

Downstream Boundary Conditions for Free-Draining Systems: With free-draining systems, if the slope is 0.004 or less, the zero-inertia engine is used for simulation. Calculations assume a free overflow (critical depth) at the downstream boundary. If the slope is greater than 0.004, calculations are performed with the kinematic-wave engine and the downstream depth is the normal depth for the calculated flow rate. This implies that the flow depth computed at the boundary can be modified by changing the simulation engine. This is demonstrated with these two scenarios, the slope was set at 0.004 in the first case and 0.0041 in the second, which causes SRFR to default to the zero-inertia and kinematic-wave engines, respectively. The difference in downstream flow depth at cutoff time is nearly 13 mm (0.5 in) but the predicted runoff rate is the same. This is because the effect of the boundary condition extends only for a short distance upstream. This effect is partly numerical and can be further reduced by increasing the cell density. The flow depth calculated at the downstream boundary

is of practical importance only when infiltration is calculated with the local wetted-perimeter option and the system is free-draining, as the minimum infiltration depth D_{min} , and therefore DU_{min} and AD_{min} , depend on that depth.

Simulation Engine and Cell Density: These scenarios illustrate the problems associated with using the zero-inertia engine with relatively steep slopes. The computed flow rates and depths oscillate with a slope of 0.003, and problems are more extreme with a slope of 0.01. In both cases, the kinematic-wave engine produces smoother flow rate and depth hydrographs but advance predictions differ slightly. Differences can be reduced by increasing the cell density with the kinematic -wave simulations. Likewise, oscillations of the zero-inertia simulations can be reduced by increasing the cell density.

Variable Slope - Effect on Simulation Engine Selection: When describing the bottom slope with a table of elevations or table of variable slopes, the average slope determines which simulation engine is selected. These scenarios illustrate problems created by that selection. In both scenarios, the upstream section of the field has a steep slope and the bottom a mild slope. The length of each section differs, such that the average slope is greater than 0.004 in the first case and less than 0.004 in the second. The second scenario produces a computational anomaly. In this case, the zero-inertia engine produces flow rate and depth oscillations in the upstream section of the field than do not attenuate downstream. This simulation will run if manually selecting the kinematic-wave engine, even though such an approach is not recommended. Increasing the cell density does not resolve the problems with this simulation.

Front End Recession and Re-Advance: The SRFR simulation engine has been occasionally used to simulate flow in filter strips, with the objective of determining the maximum distance advanced by the stream. The stream will eventually recede from both ends. This is illustrated with the first scenario. In the second scenario, inflow rate variations force the stream to recede at the downstream end, and later to re-advance. Infiltration calculations are based on the surge irrigation procedures. Downstream boundary condition changes (advance, stationary, front-end recession, re-advance) are handled by the simulator. Although front-end recession and re-advance procedures have been thoroughly tested, the simulator is not guaranteed to produce reasonable results under all conditions. Checking the volume balance error is highly recommended under these conditions.

Overflow: An overflow condition occurs when the computed depth exceeds the border or furrow depth. In such cases, the simulator limits the channel top width by assuming a vertical wall. The simulator will issue a warning at the end of the simulation, as the computed performance indicators are unreliable, more so when the overflow persists for a long time and affects a large portion of the stream. The first two scenarios compare an upstream overflow situation with one with no overflow. Use the Hydrographs (Depths) output tab to compare the resulting upstream depth hydrographs. The third scenario deals with a downstream overflow condition. Problems have been observed when simulating upstream overflows, that sometimes do not trigger a warning message. Use the Simulation Animation Window to examine potential problems with

overflow. Overflow problems can be avoided, at least in simulation studies, by increasing the border/furrow depth. Evidently, when developing design and/or operational recommendations, this issue cannot be ignored.

CHAPTER 7

EVENT ANALYSIS (FIELD EVALUATION)

An Event Analysis scenario is defined by, first, selecting the System Type, Downstream Boundary Condition, and entering the Irrigation Water Use using the controls described in Chapter 5. The procedure that will be used for the analysis is selected next, using one of the option buttons in the Start Event tab page:

- Probe Penetration Analysis
- Post-Irrigation Volume-Balance Analysis (Merriam-Keller Method)
- Two-Point Method Volume-Balance Analysis (Elliott-Walker Method)
- EVALUE

The first three procedures have specific input data requirements, which are listed in the lower-left hand side of the form using checkboxes. These checkboxes are provided for informational purposes only - attempting to uncheck any of the displayed checkboxes will cause the application to issue an error message. These analyses cannot be completed without the required data.

EVALUE scenarios have minimum data requirements but can be configured to handle optional data. Additional Field Measurement checkboxes are displayed to handle those optional data. In addition, users need to notify the application how they intend to use the optional data, either for volume balance analyses or for verification only. Details on this aspect of the configuration are provided in Section 7.4.1.

7.1 Probe Penetration Analysis

This method can be applied to all types of systems, and with any type of downstream boundary condition. In border/basin irrigation, it is assumed that the infiltrated profile is uniform across the width. With furrows, since the wetted profile varies across the furrow spacing, probe measurements are taken at both locations to determine an average penetration depth. For the procedure to calculate a final volume balance and performance, inflow and outflow hydrographs (the latter for free-draining systems) must be supplied. The procedure yields estimate of irrigation performance, but not infiltration parameter estimates. If those estimates are needed for operational analyses, design studies, or simulations, they can be developed with other procedures provided by the Event Analysis World.

7.1.1 Inputs

7.1.1.1 Common data

System Geometry inputs are as described in Chapter 5. Since hydraulic resistance and infiltration do not need to be specified for this type analysis, the Soil/Crop properties tab page is not displayed. Inflow and outflow are typically measured as part of a field evaluation. If available, they are used to calculate a final volume balance. Inflow can be specified with the Standard Hydrograph and Tabulated Inflow options only. Only time-based cutoff and cutback options can be specified with the Standard Hydrograph.

7.1.1.2 Probe Measurements tab

The probe measurement tab (Fig. 7.1) consists of two sections:

- Soil Water Depletion (SWD) Table
- Post-Irrigation Infiltrated Depths Table

Pre-Irrigation Soil Water Depletion (SWD) table The pre-irrigation soil water depletion table calculates the depth of water needed to refill the soil profile. The analysis requires prior knowledge of the Available Water Capacity of the soil, which depends on soil texture (AWC - the water held between field capacity and permanent wilting point), and the volumetric water deficit. The table allows entering deficit data from a single field location. Thus, if measurements from multiple locations are available, they should be combined into a single set of values. (Table 7.1) describes the variables used by the SWD table. The table consists of seven columns, four of which are for inputs and three for outputs. Three of the input columns are required, while one is not. The AWC can be determined from soil physical measurements or estimated from published values¹. The Soil Water Deficit (SWD) is measured from soil samples extracted with an auger. For conventional field studies, SWD can be estimated with the procedures

¹See for example Saxton and Rawls (2006)

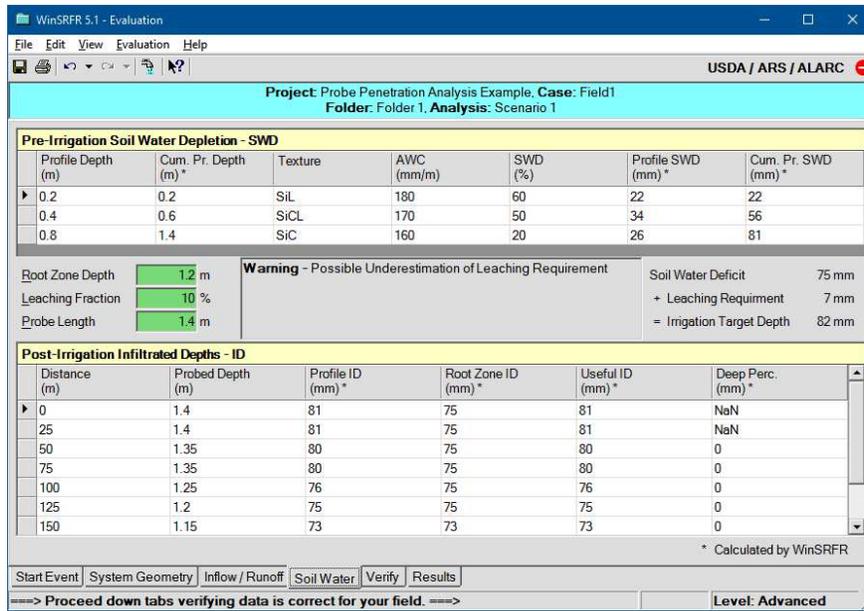


Figure 7.1: Probe Penetration analysis: Soil Water tab.

Table 7.1: Probe Penetration analysis: summary of variables for pre-irrigation soil water depletion table

Variable	Input or Output	Description
Profile depth	Input	Soil depth profile for which available soil water holding capacity and water deficit data are available
Cum profile depth	Output	Sum of depth profiles
Texture	input	Soil textural description. This field is used only for descriptive purposes, not in the calculations
AWC	Input	Available Water Capacity. The depth of water (L/L) that the given soil profile can store. The AWC can be estimated from tables or databases that relate soil texture to AWC.
SWD	Input	Soil Water Deficit. The volumetric soil water deficit in the given soil profile, expressed as a percent. For routine applications, the deficit can be estimated with the touch and appearance method (USDA-NRCS, 1998)
Profile SWD	Output	Profiled Soil Water Deficit. Deficit in the given soil layer, expressed as an equivalent depth of water
Cum SWD	Output	Cumulative Soil Water Deficit. Sum of Profile SWD.

described in USDA-NRCS (1998).

The irrigation requirement is calculated considering the soil water deficit and leaching needs. Required inputs are:

Root Zone Depth: The depth of the soil profile explored by the crop.

Leaching Fraction: The Leaching Requirement (a depth) is the product of the leaching fraction and the Root Zone SWD. The Irrigation Target Depth is the irrigation requirement, the sum of Root Zone SWD and Leaching Requirement.

Probe Length: This value is used for post-irrigation depth calculations, explained in the next section. The root zone infiltrated depth cannot be fully evaluated unless the probe is as least as long than the root zone depth. Likewise, evaluation of leaching and deep percolation losses requires a probe longer than the root zone depth. The program issues warnings in such cases.

Post-Irrigation Infiltrated Depths Table The Post-Irrigation Infiltrated Depths table consists of six columns two of which are required inputs, and four computed values. Variables are defined in Table 7.2. With the probed depth, probe length, and the SWD Table, the program determines the depth of water stored in the root zone (root zone infiltrated depth). If both the probe depth and cumulative profile depth (used to compute the soil water deficit data) are greater than the root zone depth, then the analysis will estimate the depth of water contributing to the leaching requirement, and the depth of percolation losses.

7.1.2 Execution

All calculations are conducted as the user enters the needed data in the Probe Measurements Input Tab. The Verify Tab has one input control, the Summarize Analysis button. Press this button to generate printable summaries of the inputs, outputs, and warning messages. The Summarize Analysis button will be disabled if data errors are detected.

7.1.3 Outputs

Outputs generated by the Probe Penetration Analysis are described in Table 7.3:

7.1.4 Examples

The following examples are found in the file *Probe Penetration Analysis Example.srfr*.

Scenario 1: The data for this example is displayed in Fig.7.1. The SWD is calculated using three soil layers with different textural properties, and therefore with different AWC. The table calculates the SWD for individual soil profiles, and then the total SWD for

Table 7.2: Variables for analysis of post-irrigation infiltration depths.

Variable	Input or Output	Description
Stations	Input	Distance along the field where water penetration is measured
Probed depth	Input	Depth of water penetration
Profile ID	output	Infiltrated depth in the soil profile
Root Zone ID	Output	Infiltrated depth in the soil profile within the crop's root zone
Useful ID	Output	Infiltrated depth in the soil profile contributing to the irrigation requirement (soil water deficit + leaching requirement)
Deep percolation	Output	Infiltration depth in excess of the requirement

Table 7.3: Probe Penetration Analysis: summary of outputs

Output Name	Tab	Description
Input Summary		Summary of geometry, crop and soil properties, and boundary conditions
Soil water deficit (SWD)		Same table as the SWD table in the Probe measurement tab
Infiltrated depth (ID) inputs		Same table as the ID table in the Probe measurement tab
Performance analysis table		Displays the average infiltration estimate generated from the profile measurements and from the post-irrigation volume balance (if the data is provided). Also displays the computed irrigation performance indicators
Inflow and runoff		Inflow-outflow hydrographs. Generated if the data were provided
Infiltration depths		Displays the root zone deficit, the irrigation requirement, and the measured root zone and useful infiltrated depths

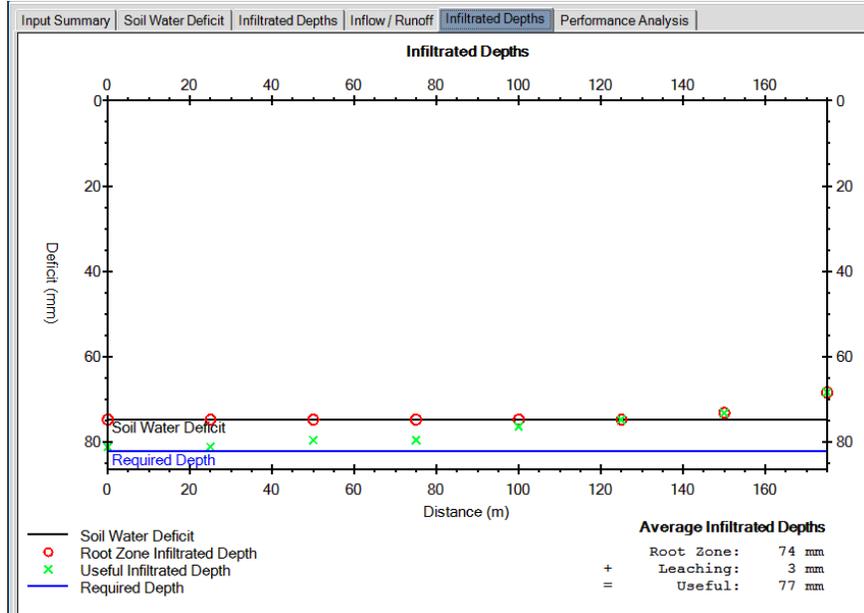


Figure 7.2: Probe Penetration Analysis: Computed infiltration depths

the cumulative soil profile. Because the cumulative profile depth (1.4 m) and the probe length (1.4 m) are both greater than the root zone depth (1.2 m), the analysis computes the root zone deficit prior and subsequent to the irrigation. The analysis also computes the depth contributing to the leaching requirement, although not in its entirety, because the irrigation target is 82 mm (75 mm of Root Zone SWD and 7 mm Leaching Requirement). This is illustrated with the data obtained at the two measurement stations closest to the upstream end of the field, where the measured probe penetration is equal to the probe length. For these stations, water could have infiltrated beyond the probed depth. Because the wetted profile length cannot be quantified from the given data at the given stations, the corresponding cells are labeled NaN (Not a Number).

Figure 7.2 depicts one of the output forms, a graph of infiltrated depths with distance. The analysis shows that the root zone was refilled except at the downstream end of the field. Leaching requirements were not met throughout of the field. Since input and outflow data are provided for this example, a final volume balance and performance indicators (application efficiency and distribution uniformity) can be calculated for this example.

Scenario 2: This example differs from the previous one in that the soil depth is less than the probe length. The data allows the determination of the final infiltration profile and deep percolation losses. Application efficiency cannot be determined, however, because no runoff data is available.

Scenario 3 This scenario differs from the first in that the probed soil depth was equal to the probe length at various locations along the field. The depth to which water penetrated cannot be determined with certainty. Thus, the final infiltration distribution and deep

percolation losses cannot be estimated.

7.2 Merriam-Keller Post-Irrigation Volume Balance

WinSRFR implements the Merriam-Keller parameter estimation method as an iterative process (Fig.7.3). At each iteration, parameters are adjusted manually with the goal of better matching the measurements to the simulation results.

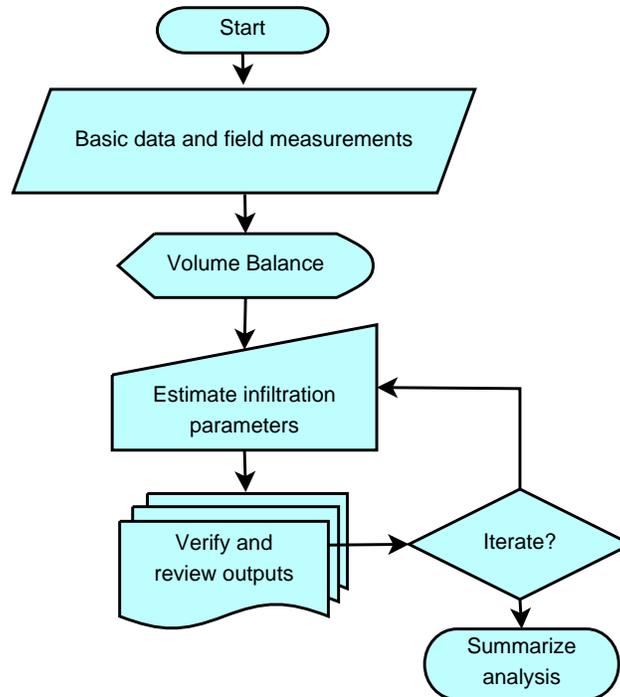


Figure 7.3: Parameter estimation with the Merriam-Keller method

7.2.1 Inputs

Common data: Since the output of this analysis is an infiltration function, the Soil/Crop Properties tab page does not display the Infiltration pane. Modeling of hydraulic resistance is limited to the Manning equation. Inflow and runoff need to be specified in the corresponding tab page. Inflow can only be described with the Standard Hydrograph and Tabulated Inflow options. Distance-based cutoff and cutback options are inapplicable and are disabled. However, time-based cutoff and cutback options remain valid. With free-draining systems, the analysis cannot be completed unless a runoff hydrograph is provided. This assumes that the stream reached the end of the field during the evaluation. Hence, the Field Measurement checkbox is checked and disabled if the downstream condition is set to open. Also, the Partial Hydrograph checkbox is not displayed, as it is assumed that the given runoff hydrograph can be used to calculate the final runoff volume.

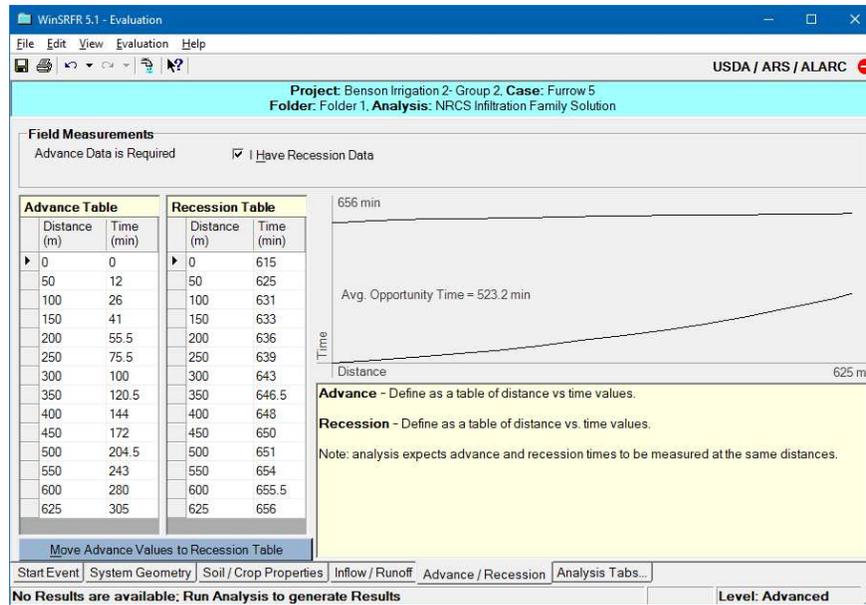


Figure 7.4: Merriam-Keller post-irrigation volume balance analysis: Advance/Recession tab

Advance-Recession: Advance measurements are the times the stream reaches a distance along the field. Recession measurements are the times that the stream disappears from the surface at a location. These data are entered through two tables in the Advance/Recession tab page (Fig. 7.4), as a distance vs. time pairs. In typical Merriam-Keller evaluations, the recession times are measured at the same locations as advance times. However, not all readings may be recorded due to unforeseen field circumstances. If advance/recession data are incomplete, WinSRFR issues a warning but calculates the opportunity times at all the given distances and interpolates the missing time values (advance and/or recession). Tabular values can be entered manually, imported from a text file, or can be copied-and-pasted from a text file or from an electronic spreadsheet. When entering the data manually, the user can copy the station distances (X) from the advance table to the recession table by pressing the button “Move Advance Values to Recession Table.” The program expects the user to provide time values at least at the upstream and downstream ends of the field and automatically enters the field length. Hence, the field length must be specified before entering data in these tables.

Because water can advance irregularly across the width of borders and basins, those times cannot be determined precisely. Estimate the fraction of wetted border/basin as a function of time and use those values as surrogates for advance (or recession) distance.

Use the plot displayed in the Advance/Recession tab page to identify anomalies in the data.

Analysis: The Analysis tab is a mechanism for switching between Input and Analysis tab pages.

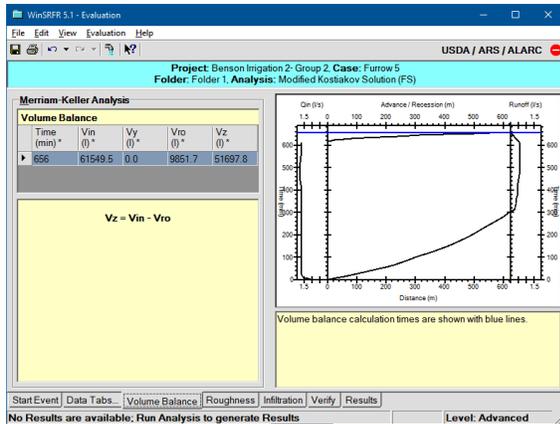


Figure 7.5: Merriam-Keller method: Volume balance tab page

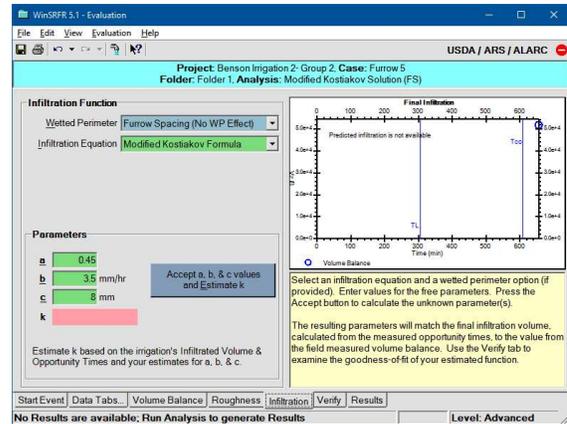


Figure 7.6: Merriam-Keller method: Infiltration tab page

7.2.2 Analysis

Use these tabs to carry out the analysis outlined in the flow chart of Fig. 7.3.

Volume balance: This tab page (Fig. 7.5) displays a graphical summary of the Inputs and a tabular summary of the volume balance analysis. The post-irrigation volume balance will not be calculated if the data are incomplete and an error condition will be reported. The volume balance summary is provided for informational purposes only, and no user inputs are required.

Infiltration: This tab page (Fig. 7.6) is used to estimate the infiltration function. The analysis matches the volume balance calculated infiltration with the value computed by integration of the infiltration profile. An infiltration function is defined by, first, selecting an infiltration modeling approach and, second, by specifying or calculating the model parameters (see Section 5.4.2).

Infiltration function: With borders and basins, the infiltration equation defines the modeling approach. With furrows, a wetted perimeter option is selected first, and an infiltration equation is selected afterwards. The wetted perimeter option limits the infiltration equation choices. Wetted perimeter and infiltration equations are selected using drop-down controls, shown in Fig. 7.6

Parameters: The Merriam-Keller method estimates only the parameter k , when modeling infiltration with the Kostikov, Modified Kostikov, and Branch equations. The method can also be used to estimate an infiltration family, for which all parameters are pre-defined. Depending on the selected infiltration equation, other parameters need to be provided as inputs. The Parameter pane displays input boxes for those parameters. The boxes display with a white background when storing default values and in green when storing user-provided data. The parameter(s) to be estimated will be displayed with a pink background. After editing the input fields, press the Estimate button.

Final infiltration: The graph shows the infiltration volume calculated from volume balance in a blue circle. After estimating an infiltration function, the graph also displays the volume calculated from integration of the infiltration profile, which is identified with a red X. That marker should match the blue circle, except when using the NRCS equation. In that case, and since the parameters are predefined, the infiltration integral can only approximate the volume balance value.

Verify: Press the Verify and Summarize button in this tab page to conduct an unsteady flow simulation with the estimated function. Simulation results will then be compared with the available measurements. Use the verification outputs, described below, to adjust the modeling approach and/or the parameter values, by trial-and-error to better match the predicted advance times, recession times, and runoff hydrograph to the observed ones. The adjustment process requires an understanding of how individual infiltration parameters and uncertain inputs, in particular hydraulic roughness, affect the predictions. Tests should be conducted to assess the sensitivity of the solution to uncertain inputs.

7.2.3 Outputs

Outputs generated by the analysis are summarized in Table 7.4:

Table 7.4: Outputs of the Merriam-Keller analysis

Output Tab	Description
Input Summary	Summary of inputs
Hydraulic Summary	Combination graph showing measured and predicted advance-recession times, runoff data (if applicable), and predicted final infiltration
Volume Balance	Summary of volume balance calculations
Infiltration Function	Estimated infiltration function as a function of time. Note that the left vertical axis represents A_z while the right represents A_z/W (borders) or A_z/FS (furrows).
Performance Summary	Efficiency and uniformity indicators
Parameters and Goodness-of-Fit	Parameter values and goodness-of fit statistics computed from observations and simulation results

7.2.4 Examples

The procedure is illustrated with examples in the file *Merriam-Keller Analysis.srfr*. The data were reported by Elliott (1980), and are identified as Benson Farm, Irrigation 2, Group

2, Furrow 5 (Benson 2-2-5). The field length is 625 m. The data set includes advance and recession time measurements at 25 m intervals, field elevations at each of these stations, cross-sectional data measured with a profilometer at about 100 m intervals, and inflow and outflow hydrographs. Since runoff was not measured until the end of the irrigation and recession was not measured near the end of the field, some measurements were assumed in this file in order to calculate the final volume balance. An average trapezoidal cross-section was defined from the available measurements (see Section 5.2.2).

The *Event Analysis* folder (Folder 1) contains three scenarios, each developed with a different wetted perimeter and infiltration equation combination. The first scenario uses the NRCS wetted perimeter and Infiltration Families. The second uses the furrow spacing wetted perimeter option in combination with the Modified Kostiakov equation. The last scenario also uses the Modified Kostiakov equation, but with the Representative Upstream Wetted Perimeter option.

Solving the post-irrigation volume balance parameter estimation problem with the NRCS infiltration families is straightforward because no additional inputs are required. Generate a solution simply by pressing the Estimate button. Since the NRCS infiltration families are fixed relationships, V_z^* only approximately matches V_z . Consequently, different phases of the irrigation event may not be well predicted with this solution. More importantly, the solution depends on the assumed value for the roughness coefficient (through Eq. 5.18). Since wetted-perimeter increases with n , infiltration rates (i.e. the Infiltration Family number) must decrease to match the V_z from post-irrigation volume balance. To illustrate this point, develop NRCS infiltration family solutions for Manning n values of 0.015, 0.03, and 0.04 ($n = 0.04$ is typically recommended for bare furrows). The infiltration family (IF) estimates are, respectively, 0.8, 0.7 and 0.6. These are relatively large changes in infiltration considering the small changes in the Manning n . Validation results and an understanding of how infiltration and roughness affect the computed outputs are needed to narrow down the solution.

Advance times depend on both infiltration and hydraulic resistance, but those effects cannot be differentiated without independent flow depth measurements. If inflow is relatively stable and runoff is measured relatively long after the final advance time, the surface volume is nearly constant with time. Under such conditions, the runoff hydrograph is independent of roughness and is directly related to near-steady infiltration rates, which is what the NRCS infiltration families represent. With free-draining systems, recession times depend partly on near-steady infiltration rates, but mostly on the surface volume at cutoff and, therefore, on roughness. It follows from these arguments that for this example, runoff rates and recession times provide more reliable information about infiltration and hydraulic resistance than advance times.

To analyze these effects, copy and paste each of the Event Analysis scenarios described above to a Simulation World folder. Execute those scenarios and contrast the outputs with the field measurements (the NRCS scenario in the Event Analysis world) using the Data Comparison tool. Figure 7.7 shows the (a) advance/recession time and (b) the runoff rate graphs, as displayed by the Data Comparison tool. Recession times are well predicted with n

= 0.02 and IF=0.8, but the runoff is under-predicted. In contrast, runoff is better predicted with $n = 0.04$ and $IF = 0.6$, but recession times are over-predicted. The three proposed solutions predict nearly the same advance times for distances less than 500 m and differ mostly in the last 125 m. These results suggest that a combination of $n = 0.02$ and $IF = 0.7$ or $n = 0.03$ and $IF = 0.6$ could improve the simulation results. Use again simulation to test these cases. You will find that the first option predicts runoff rates and recession times best, but at the cost of under-predicting advance times. The implication is that a function similar to the 0.7 infiltration family, but with larger infiltration rates at short times, would describe the infiltration conditions for this field best.

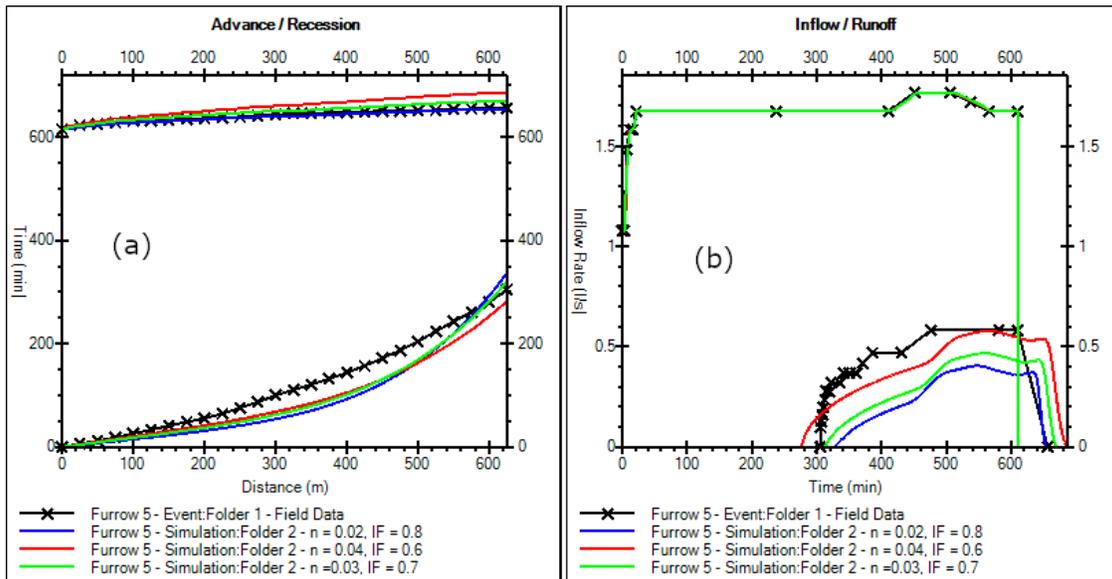


Figure 7.7: Merriam-Keller analysis: outputs from Example 1

The Modified Kostiakov (Eq. 5.8) infiltration equation (in combination with either the FS or RUWP wetted perimeter option) can model the infiltration process with greater flexibility than the infiltration families. In principle, fitting the Modified Kostiakov equation is difficult because four parameters need to be estimated (five, if roughness is also unknown). However, the estimation can be simplified by first fixing the value of the exponent a . Reasonable values are suggested by approximate infiltration solutions developed from porous media theory, in particular Philip, 1957 ($a = 0.5$) or Furman et al., 2006 ($a = 0.45$). The analysis can be further simplified by prioritizing the estimation of b , minimizing the contribution of the transient component $k \cdot t^a$, and using c to explain most of the infiltration at short times. Such an approach is justified by the uncertainty of infiltration measurements during the advance phase in comparison with the runoff phase, as explained earlier.

In the Event Analysis scenario labeled Modified Kostiakov Solution (FS), the exponent was set to $a = 0.45$. The Manning n calculated in the first scenario was adopted, as the infiltration equation should not affect n . A solution for k was computed first with c set to zero and b to an arbitrary value. b was further adjusted based on verification results, by

comparing the observed and simulated runoff hydrograph. Note that an unreasonable b value can force k to be negative. Thus, verification should be conducted only if k is positive. Once runoff was adequately predicted, c was adjusted to match the advance. Both parameters were then fine-tuned. Some experience is required to carry out the trial-and-error process effectively. The solution displayed in the scenario was calculated by setting $b = 3.5$ mm/h and $c = 9$ mm, but the measured advance, recession, and runoff may be reproduced equally well with other combinations of parameters. As an example, compare the resulting performance and goodness-of-fit indicators calculated with $b = 3$ mm/h, $c = 6$ mm and $b = 4$ mm/h, $c = 11$ mm. Compare also the infiltration functions with the function developed in the first scenario. Infiltration rate predictions differ only at small times.

The third scenario uses the Representative Upstream Wetted Perimeter option. A solution can be found using the process described in the previous paragraph. Alternatively, find a solution with the furrow spacing option first and then change the wetted perimeter option. The software will issue a warning and offer to adjust the parameters for the new wetted perimeter. The resulting infiltration function is the same as that computed in the previous scenario, but only for the hydraulic conditions of the example. If any of those conditions change (cross-section, slope, Manning n , inflow rate), the functions and, consequently, hydraulic performance predictions will differ.

7.3 Two-Point Method

Figure 7.8 summarizes the Two-Point method, as implemented in WinSRFR. The process is iterative, and requires adjustments not only to the estimated parameters but also to the volume balance calculations, as the surface and subsurface shape factors (Eqs. B.2 and B.4, respectively, in Appendix B.1) need to be updated every time the infiltration parameters change.

7.3.1 Inputs

Common Data: Select the Elliott-Walker two-point method with the corresponding option button in the Start tab page. The Field Measurements used by the method are listed in the form. Inflow Hydrograph and Advance Times are required inputs, while a Runoff Hydrograph is optional. The Soil/Crop Properties tab page only displays the Roughness input pane, as the objective of this analysis is to estimate infiltration. Modeling of hydraulic resistance is limited to the Manning equation. Inflow and runoff need to be specified in the corresponding tab. Inflow can only be specified with the Standard Hydrograph and Tabulated Inflow options, With a Standard Hydrograph, cutback options are inapplicable and only time-based cutoff is allowed. The analysis can be completed with free-draining systems without runoff data. If runoff data are available, only a partial hydrograph can be provided. If detailed runoff measurements are available, the EVALUE procedure should be used instead since those measurements are used to calculate additional volume balance equations for the post-advance phase.

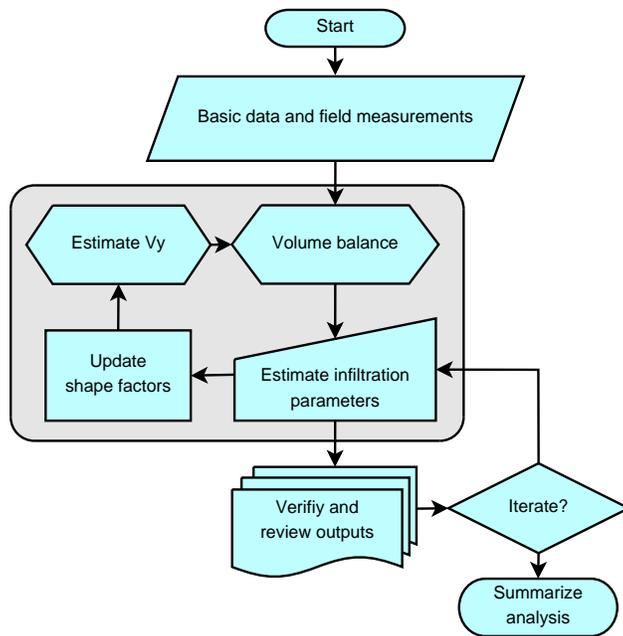


Figure 7.8: Parameter estimation with the Two-Point method

Advance: Use this tab page to enter the two advance distance-advance time pairs required by the two-point method (Fig. 7.9). The recommended approach is for the measurement stations to be located at half and full field length, but other distances are allowed. Advance times should always increase with distance and the resulting power advance function (shown in the graph) should have an exponent r less than unity. Exponent values close to or greater than unity or less than 0.5 suggest anomalous data or highly non-uniform field conditions (infiltration, inflow rate, etc.). Such values can lead to problems with the estimated parameters. Check the advance plot for data anomalies.

7.3.2 Analysis

The iterative process outlined in Fig.7.8 is implemented through the Analysis tabs, which are described next

Volume Balance: This tab page (Fig. 7.10) summarizes the results of the volume balance analysis. The page has no editable fields and is provided for informational purposes. The estimated parameters become increasingly sensitive to inputs required for the calculation of surface volume as the surface volume increases in relation to the total applied volume.

Surface Volume (estimated) This tab page (Fig. 7.11) displays the details of the surface volume (V_y). These values are computed with Eq. B.2. Since calculations depend on the Manning n , controls are provided for editing that value. Try alternative reasonable values for n to assess how they affect volume balance results.

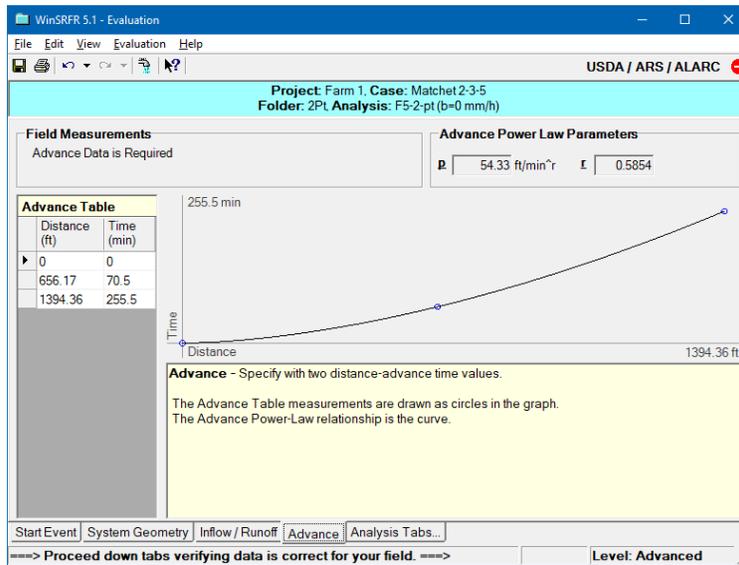


Figure 7.9: Two-point analysis: Advance tab

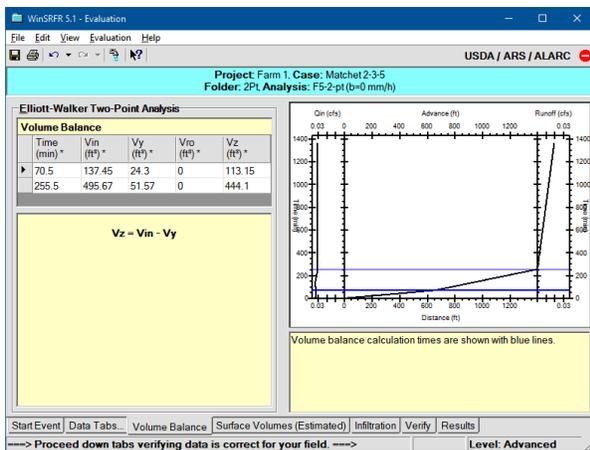


Figure 7.10: Two-point analysis: Volume Balance tab

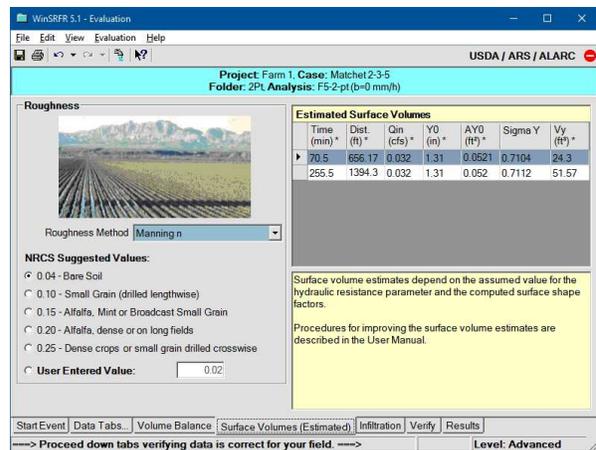


Figure 7.11: Two-point analysis: Surface Volumes (Estimated) tab

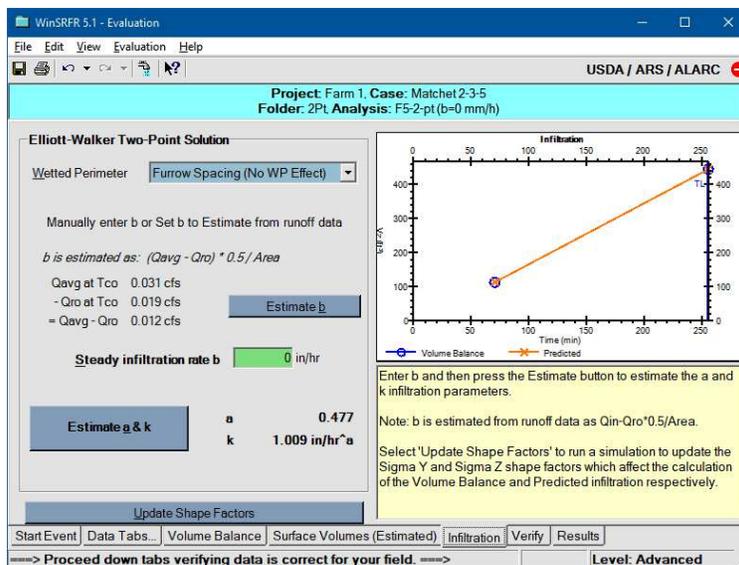


Figure 7.12: Two-point analysis: Infiltration tab

Conventional two-point calculations (Elliott and Walker, 1982) assume a constant σ_y (0.77), independent of hydraulic conditions and time. Estimation results are not very sensitive to this parameter when V_y is small in relation to the applied volume but are very sensitive when V_y is relatively large (Bautista et al., 2012b). The WinSRFR implementation of the Two-Point Method includes relationships for generating an initial estimates for σ_y , and a mechanism for refining those values from simulation results. Use this tab page to inspect the estimated σ_y values, and to test the sensitivity of the estimated surface volume to the Manning n . Use the Infiltration tab page to refine the σ_y .

Infiltration: The estimation is conducted with this tab (Fig. 7.12). Use the following controls sequentially:

Wetted Perimeter: If working with furrows, select a wetted perimeter option with the corresponding drop-down control. Only two options are available for this type of analysis, Furrow Spacing or Upstream Wetted Perimeter. This control will not be displayed if working with borders/basins.

Estimate b: Press this button to estimate b from the given inflow and runoff hydrographs. The button will be disabled if the data set does not include a runoff hydrograph, in which case a value will have to be provided manually. The estimate is calculated using a variation of the method proposed by Walker and Skogerboe (1987, p. 105):

$$b = \psi \frac{\overline{Q_{in}} - Q_{ro}(t_{co})}{L \cdot FS} \quad (7.1)$$

In this expression $\overline{Q_{in}}$ is the average inflow rate up to the cutoff time T_{co} , Q_{ro} is the outflow rate measured at or prior to T_{co} , L the field length and FS the

furrow spacing (substituted by the border width W with borders). In the original method, the denominator of Eq. 7.1 is only L and the parameter b (identified as f_0 in that publication) has dimensions of area/time. Here it has dimensions of length/time. Also, the original method assumes that Q_{ro} is measured at steady-state. The infiltration rate often continues to decline for times much longer than the duration of typical irrigation events. Hence, 7.1 assumes that the system is not at steady-state and reduces the value of b with the empirical parameter ψ ($\psi = 0.5$).

Steady-infiltration rate b : This text box displays the calculated b or is used to specify a value if one cannot be calculated². This box is used also to update b manually, based on the verification results (see Fig. 7.8).

Estimate parameters: Calculate k and a by pressing this button. If calculations are successful, the resulting k will be positive and the exponent will also be positive and less than unity. The Errors and Warnings window will generate messages if the application detects missing or inconsistent data. A negative value for any of the parameters is an indication that the b used for the calculations is too large, or that the power advance exponent is unusual. The value of b can be adjusted, as explained in the examples section. An unusual advance exponent, which is displayed in the Advance tab, cannot be corrected.

Update shape factors: When this button is pressed, the application calculates new shape factors from simulation results with the current infiltration parameter estimates. Since this action updates the volume balance results, the infiltration parameters need to be recalculated.

Verify: Pressing the Verify and Summarize Analysis button prompts the application to conduct an unsteady simulation with the estimated infiltration function and to compare simulation results with the available measurements. Use the verification results to adjust b and, subsequently, k and a . A mismatch between observed and predicted advance times is an indicator that the shape factors need to be updated. Return to the Infiltration tab page to update those values. Accurate prediction of the advance times is a necessary but not sufficient measure of the reliability of the estimated infiltration function. Reliability improves when, in addition to the advance times, the predicted and measured (if available) runoff hydrograph are also in reasonable agreement. Be aware that advance predictions strongly depend on the assumed Manning n , but runoff predictions do not, if the system is under steady-state.

7.3.3 Outputs

The following table summarizes the outputs of the Two-Point Analysis:

²An estimate for b may be available from field evaluations conducted under similar soil conditions, from the soil texture, or from published data. Make sure, however, that the dimensions of the reported b are consistent with those required by WinSRFR

Table 7.5: Outputs of the Elliott-Walker two-point analysis

Output Tab	Description
Input Summary	Summary of common inputs
Hydraulic Summary	Combined graph showing the inputs and simulation results, including advance, runoff, and final infiltration profile
Volume Balance	Tabular summary of the volume balance calculations
Infiltration Function	Graphical display of the infiltration function (time vs. depth)
Performance Summary	Summary of performance indicators
Parameters & Goodness-of-fit	Estimated parameters and statistics computed from observations and simulation results

7.3.4 Examples

Example are provided in the *Two-Point Analysis.srfr file*. Execute the scenarios and compare with the Data Comparison Tool.

The data for these examples was reported by Elliott, 1980 as Matchett Farm, Irrigation Number 2, Group Number 3, Furrow 5 (Matchett 2-3-5). The furrow is 425 m (1395 ft) long and has an average slope of nearly 1%. The data set contains detailed advance times, recession times, field elevations, cross-sections, inflow and runoff hydrographs, and some flow depths and corresponding top widths. Only a subset of these data are used for this analysis.

The folder *2Pt (Observed)* contains three Two-Point scenarios. Each uses as input: the average field slope; average cross-sectional parameters calculated from the cross-section data (see Section 5.2.2); an assumed value for the Manning n (0.04); the complete inflow hydrograph; the advance times measured at 200 m and 425 m for its calculations and a single outflow flow value measured just prior to cutoff time. With these data, the application computes $b = 1.92$ mm/h (0.08 in/h) (by pressing [Estimate \$b\$ from steady runoff data](#)). For comparison purposes, scenarios were created with b specified manually, as $b = 0$ and 3.84 mm/h. The latter is the value computed with Eq. (7.1) with $\psi = 1$. Simulation scenarios were created from each of these solutions.

Using the Data Comparison tool, select the F5-2pt ($b = 0$ mm/h) scenario in the 2Pt (Observed) folder and its counterpart in 2Pt (Simulated) folder. Select the Advance tab and un-check the Recession box. Notice that the simulation matches the two advance observations very closely.

Next, select the scenarios, $b = 1.92$, $b = 3.84$ in the *2Pt (Simulated)* folder. Compare

the predicted advance for all scenarios with the observations. Inspect now the Infiltration Function, Inflow/Runoff, and Infiltration tabs. Figure 7.13 displays these results. All three solutions match the advance data (a) equally well but produce very different infiltration functions (b), runoff hydrographs (c), and final infiltration profiles (d). It should be clear that goodness-of-fit of the infiltration function estimated with the Two-Point method cannot be judged by simply comparing the simulated advance with the two advance measurements.

The single outflow measurement used in the calculations provides an additional measure of goodness-of-fit for the three proposed solutions. The two values provided in the Runoff Table are represented as symbols joined by a line in Fig. 7.13c. The runoff rate at 1364 min is visible on the right hand side of the graph. The solution computed with $b = 1.92$ mm/h predicts this single runoff rate value most closely.

Surface volume calculations are sensitive to the assumed hydraulic roughness parameter. This issue is examined with the scenarios in the *Sensitivity Tests* folder. Solutions were developed with $n = 0.02$ and $n = 0.06$. Compare those results with the ones obtained with $n = 0.04$. The predicted recession, runoff, and final infiltration profile differ slightly, but estimates of application efficiency and distribution uniformity are essentially the same. Likewise, the resulting infiltration functions predict similarly at least for infiltration depths less than about 150 mm (6 in), despite differences in the computed parameters.

For this example, the Two-Point solutions can be contrasted with the detailed advance, recession, and runoff measurements available in the Complete Data set scenario. Evidently, the Two-Point method would not be recommended for parameter estimation if such an extensive data set is available. Execute the F5-Merriam-Keller scenario, using the inputs provided. Compare then this event analysis scenario with the simulation scenario generated with $b = 1.92$ mm/h. These results should confirm that that particular two-point solution reproduces the observed irrigation event fairly well.

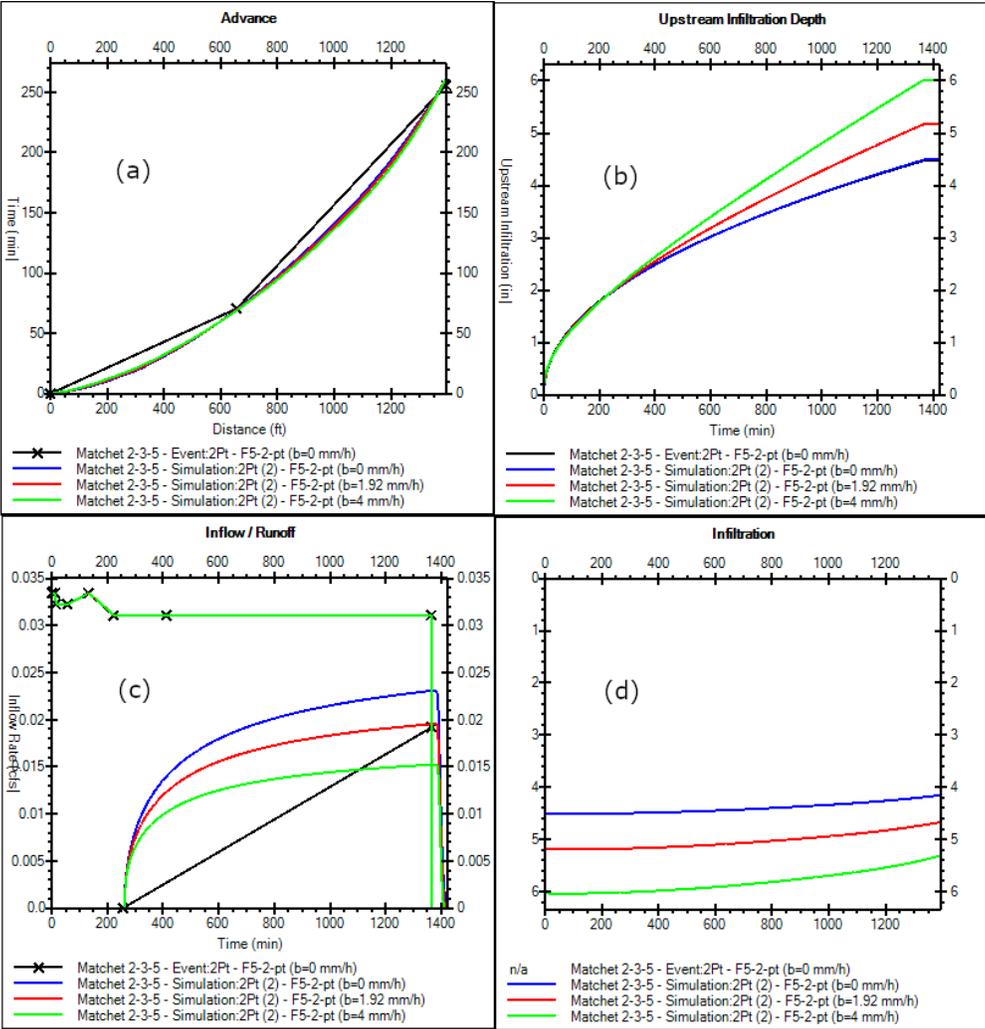


Figure 7.13: Two-point analysis: outputs from the Matchett2-3-5 example.

7.4 EVALUE

The EVALUE component consists of three interrelated procedures, illustrated in Fig. 7.14:

1. The first procedure, enclosed in the light green box, is used to estimate the parameters of empirical infiltration functions. This part of the analysis assumes that infiltration depends on opportunity time only. Depending on the user's objectives and the available data, an EVALUE analysis may use only this first procedure.
2. The second procedure, identified by the light pink box, is used to estimate the hydraulic resistance coefficient. This part of the analysis can only be carried out after completing the first step and only if the data includes measured flow depths.
3. The last procedure (in light yellow) estimates the parameters of flow-depth dependent infiltration equations, both semi-physical and empirical. This procedure uses simulated flow depth hydrographs, computed with the infiltration parameter estimates derived in the first stages of the analysis and, ideally, with a hydraulic resistance parameter calibrated from measured flow depths. However, this last part of the analysis can be conducted without first calibrating resistance, by assuming a value for the resistance parameter. Users must then examine the sensitivity of the flow-depth dependent infiltration parameters to a reasonable range of roughness parameter values.

In the flow chart, the color of the connector lines identifies data-dependent paths in the analysis. The black connector lines represent the minimum path that needs to be followed to complete the first part of the analysis. When dealing with typical evaluation measurements - inflow rate and advance times, and perhaps runoff rates and recession times - surface volumes needed for volume balance calculations will be estimated hydraulically. In those cases, the analysis will also follow the blue connector lines and additional iterations will be required as volume balance calculations need to be adjusted every time the infiltration parameters change. This is because surface volume estimates depend on estimated parameters through the surface shape factors (see Section 2.2). In addition, the subsurface shape factors may need to be adjusted if Vz^* (Eq. B.3) is calculated using the power law integral. The availability of detailed flow depth data simplifies the analysis because surface volumes can be calculated from flow depth profiles. This alternative path in the analysis is represented by the red connector lines.

Red lines connect the processes used to estimate the hydraulic resistance parameter as this part of the analysis requires measured flow depths. This type of analysis can be conducted with a limited set of measurements in comparison to those required for surface volume determinations. If the data includes flow depths, but those measurements are used only for the estimation of hydraulic resistance, the analysis will initially follow black and blue connector lines, and then the red lines. It will then need to return to re-estimate the infiltration parameters, as updates to the roughness parameter will change the volume balance calculations. This is indicated by the red connector line on the left side of the flow chart. If the flow depth measurements are used for both the estimation of infiltration and roughness parameters, then the analysis does not require further adjustments to the volume balance

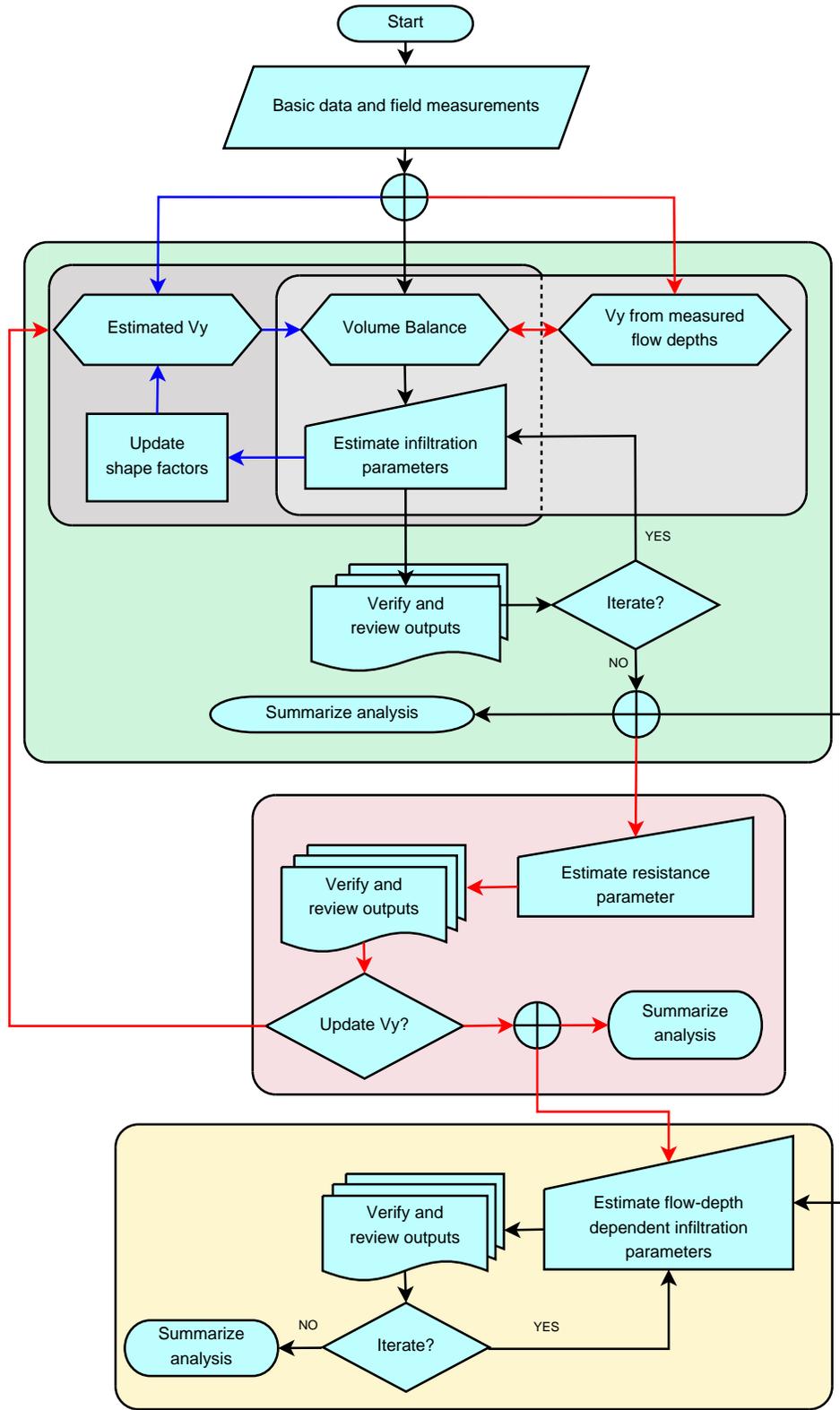


Figure 7.14: Parameter estimation with the Evaluate method

calculations and can either conclude or proceed to the third stage.

As was previously explained, the estimation of depth-dependent infiltration parameters will be conducted, ideally, with the support of measured flow depths, but this procedure can be used without those data. Thus, the connection to this last stage is either with a red line, emanating from the second stage, or a black line, emanating from the first stage. The black connector lines in the last procedure denote the fact that the procedure applies to either case.

7.4.1 Inputs

Start: The Start tab page (Fig. 7.15) displays checkboxes for the required and optional Field Measurements. An EVALUE analysis requires a measured Inflow Hydrograph and one or more Advance Times, hence those checkboxes are checked. Use the checkboxes to identify the optional data available for the analysis. Data entry forms will be displayed only for the checked Field Measurements. An analysis will fail to execute and the application will issue Error Messages if those data forms are not populated. For each selection, the application displays an additional checkbox below the label Use for VB calc. Check those items that will be used in volume balance calculations. Data that are not used for volume balance analyses will be used for verification.

As an example, the application needs to be notified if incomplete or sparse runoff measurements will be used for volume balance analyses. With only a few measurements, it may not be possible to determine the runoff volume reliably and incorporate those data in the volume balance analysis. However, those measurements can still be compared with the runoff rates predicted with the estimated parameters. Therefore, they can still be used to further adjust the infiltration function.

Another example is the use of flow depth measurements. Those data can be used to determine the surface volume at various stages during the irrigation event. Check the Use for VB calc checkbox only if measurements were collected with relatively high resolution in space and time. If the data is insufficient for surface volume calculations, they can still be used to refine the roughness parameter estimate, or to test the adequacy of the estimated infiltration function.

Advance/Recession This tab page is similar to the one shown in Fig.7.4. The Recession Table will be displayed only if the Recession Times checkbox in the Start tab page is checked. The form plots the data and calculates a power advance relationship which is used to integrate the infiltration profile (Eq. B.4). The parameters of this equation are computed using non-linear optimization, but they can be modified manually. Manual adjustments to these parameters are useful when the measured advance times are very erratic.

Flow Depths: Flow depths are used in EVALUE for surface volume calculations and calibration of the roughness parameter. Since such analyses involve comparisons of water

Event Analysis (Field Evaluation)

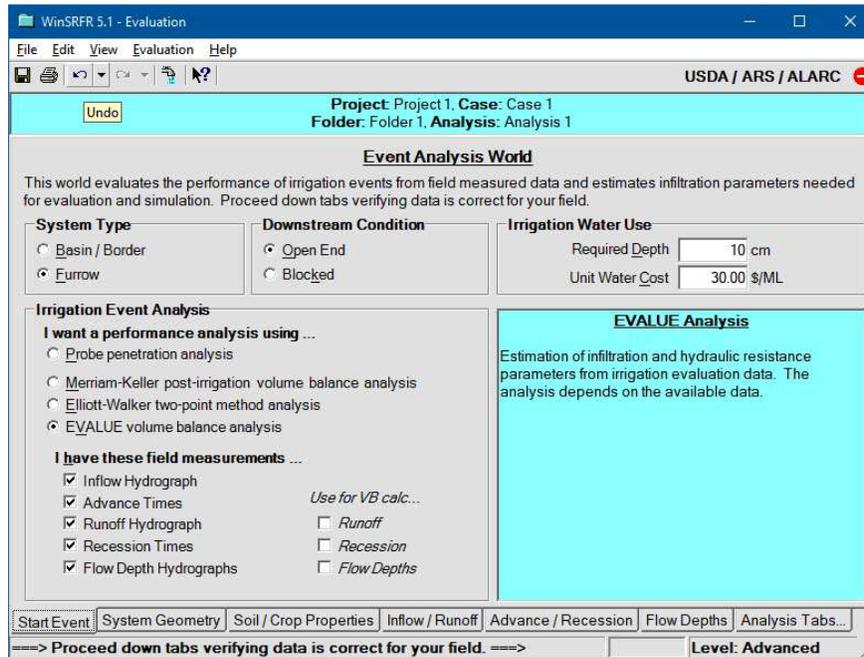


Figure 7.15: EVALUE analysis: Start tab

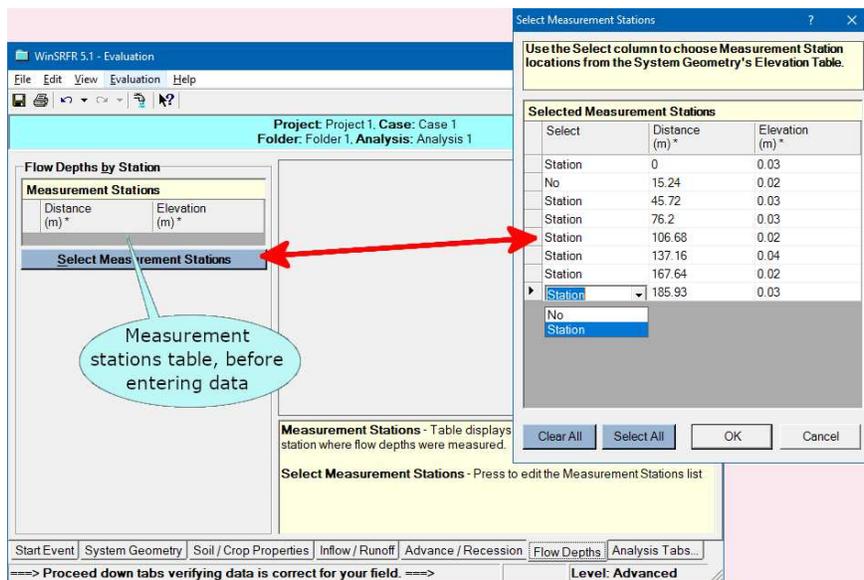


Figure 7.16: EVALUE analysis: Flow Depths tab page

surface elevations, field bottom elevations need to be provided first in order to properly interpret the flow depth measurements. Use the Elevation Table option in the System Geometry tab to provide field elevation data. Field elevations need to be provided even if using the depth data only for verification purposes.

Advance times (and recession times, if measured) need to be entered also prior to inputting flow depths. Those times must be given at all locations with depth measurements. Flow depth data must be consistent with advance and recession data. Thus, the initial flow depth time and the advance time must be the same at any station. Likewise, if recession times are measured, they must match the last depth measurement time reported for the corresponding station. The application will issue warnings or error messages if the data are inconsistent.

Figure 7.16 depicts the Flow Depths tab page, as initially displayed. Flow depths are specified with two table controls, Measurement Stations and Flow Depths. The former table is also shown in the figure. The Flow Depths table is displayed only after specifying the depth measurement stations with the first table. In addition, the tab page displays plots of the measured depth hydrographs. Instructions for editing each table are provided next.

Measurement Stations: This table identifies the distances along the field with depths measurements. It is populated with the modal form shown in Fig. 7.16, which is displayed by pressing the Select Measurement Stations button. The Select Measurement Stations table is populated with data from the Field Elevation Table. In an evaluation, field elevations may be measured at more locations than those used to measure flow depths. Thus, the table has a column labeled Select that is used for selecting elevation stations with (Station) and without (No) depth measurements, as illustrated in Fig. 7.16. Use the Select All and Clear All buttons to select or deselect all available field elevation stations as depth measurement stations or use the drop-down control in the Select column to change the status of individual stations. After completing the selections, press OK to return to the Flow Depths tab page and transfer the data to the Measurement Stations table.

Flow Depths: The Flow Depths table is used next to enter the time versus flow depth data, one station at a time. Select first the station to edit by clicking on a row in the Measurement Stations table (Fig. 7.17). The Flow Depths table identifies the station to be edited. For example, if a station is available at a distance of 0 m, then the lower table will be labeled Flow Depth for Station 0 m. Although the hydrograph data can be populated manually, the recommended approach is to use copy-and-paste, either from a spreadsheet or a text file, or to import from an existing text file (File/Flow Depths for Station at XX/Import From File). Review the corresponding hydrograph plot for potential data anomalies.

Event Analysis (Field Evaluation)

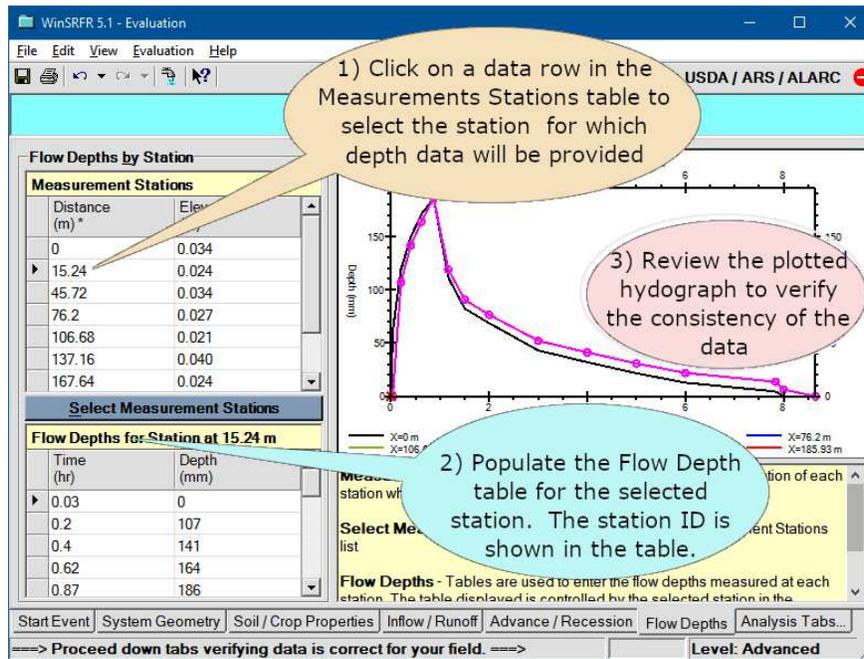


Figure 7.17: Entering flow depth data with the Measurement Stations and Flow Depth tables

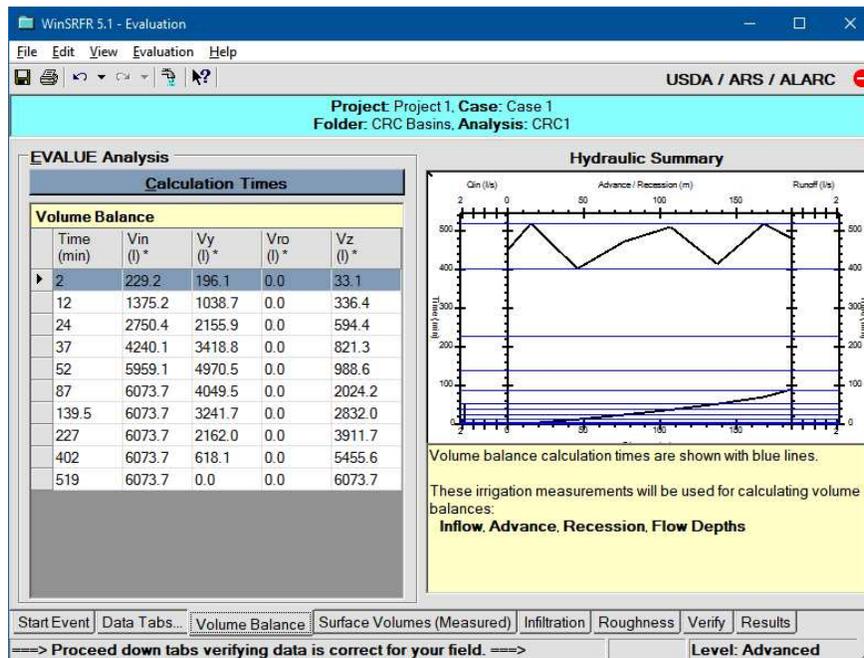


Figure 7.18: EVALUE analysis: Volume Balance tab

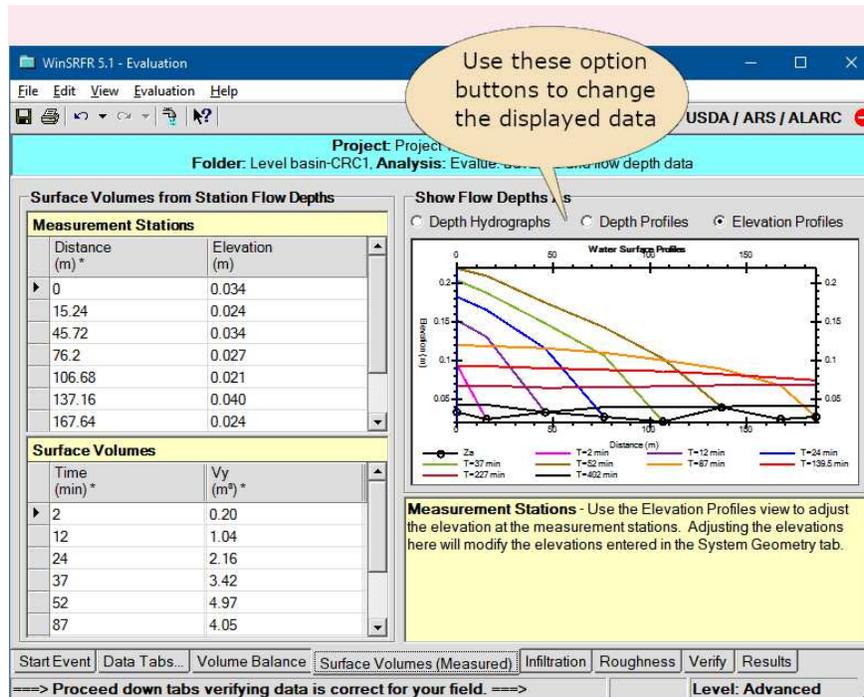


Figure 7.19: EVALUE analysis: Measured Surface Volumes tab

7.4.2 Analysis

Volume balance: Volume balance calculations are summarized in the Volume Balance tab page (Fig. 7.18). In contrast with the corresponding tab pages for the Merriam-Keller and Two-Point Methods, the number of volume balance equations used in an EVALUE analysis depends on the available data. They can be selected by the application by pressing the Volume Balance Calculations Times button or the user can specify those times or modify the times suggested by the program, but only as allowed by the data. Rows can be added to the table, or deleted. The Time column in the Volume balance table is the only editable field and other columns are updated as the time values change. The application is programmed to select 12 or less calculation times. This is reasonable if the data does not show any anomalies or irregularities. If the advance time and runoff measurements are very erratic, additional calculation times can be added manually.

The tab page summarizes graphically the advance time, recession time, inflow, and runoff measurements (hydraulic summary) and overlays the selected volume balance calculation times as horizontal blue lines.

Surface Volumes (Measured) This tab page (Fig. 7.19) will be displayed only if flow depth data are provided and the VB calc checkbox in the Start tab page is checked. The top table replicates the Measurement Stations shown in the Flow Depths tab page. The bottom table summarizes the computed surface volumes. The tab page provides three types of graphical outputs: depth hydrographs, depth profiles, and water surface

elevation profiles. The latter combine the water depths with the field elevations. Use these graphs to identify anomalous data. The elevation profiles can be used to identify potential errors with the measured field elevations, but mostly when the field bottom average slope is small³. If errors in the flow depth and/or field elevation data are detected, use the corresponding tab pages to correct them.

Surface Volumes (Estimated): This tab page replicates the one used for the Two-Point Analysis (Fig. 7.11). It summarizes the estimation of V_y and is displayed partly for informational purposes and partly to allow the user to examine the sensitivity of the computed values to the roughness parameter and to the σ_y . Use the Roughness pane to edit the roughness parameter, typically expressed with the Manning n . The only editable column in the Estimate Surface Volumes table is σ_y . These values affect the calculation of V_y , directly through Eq. B.2, and indirectly, as they are used to calculate the upstream depth, and therefore, $A_y(0)$. σ_y values can be edited manually, but it is best to let the application update those values. The update process is explained later.

The Estimated Surface Volumes table will display zero values at times when V_y cannot be computed. This may indicate inconsistent data or that the user entered an invalid calculation time manually. As an example, with blocked-end irrigation systems V_y cannot be hydraulically estimated at any time after the stream reaches the end of the field because the computational procedures are invalid when the stream is under backwater effects. Volume balance calculation times that result in anomalous surface volumes need to be deleted from the Volume Balance table (in the Volume Balance tab page).

Infiltration: Use this tab page (Fig. 7.20) to estimate an infiltration function by minimizing the difference between the volume balance calculated infiltration and the values computed by integration of the infiltration profile. Standard users can estimate the parameters of empirical infiltration equations dependent on opportunity time only. Those functions are identified in the form as Standard Infiltration Functions. Advanced users can subsequently estimate the parameters of Flow-Depth Dependent Infiltration Functions with this tab page. Controls in this tab page are used as follows:

Select Standard Infiltration Equation The first step is to select an infiltration modeling approach. This is done with the drop-down controls in this pane. If working with furrows, select first a wetted perimeter option (Furrow Spacing, NRCS, or Upstream Wetted Perimeter). Only the Infiltration Equation selector will be displayed with borders/basins.

Parameters: Edit next the equation parameters. The number of parameters to edit depends on the selected infiltration modeling approach. The parameters can be edited with the displayed text boxes, but the recommended approach is to use

³If the field is steep, elevation nonuniformities will likely be small relative to the total elevation drop shown on-screen.

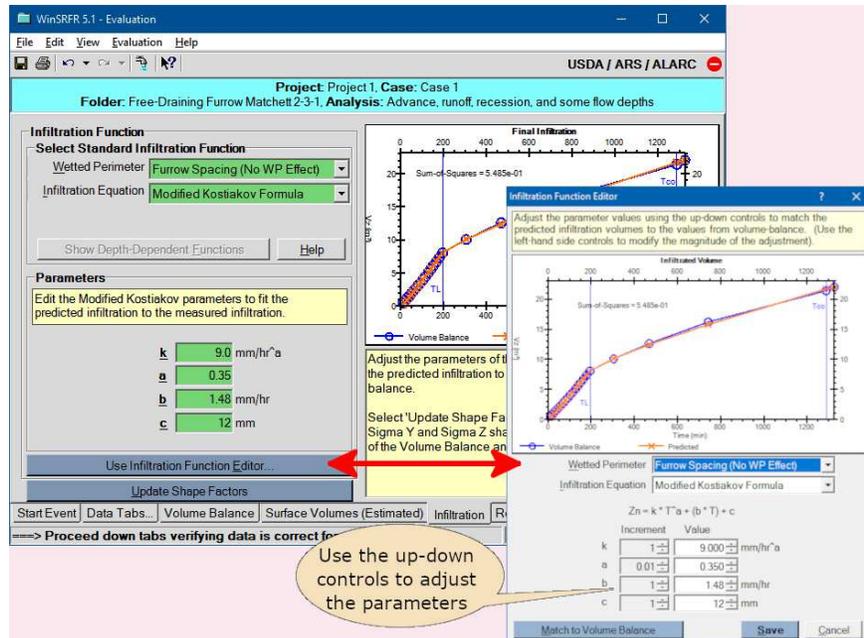


Figure 7.20: EVALUE analysis: Infiltration tab

instead the Infiltration Function Editor, which is displayed by pressing the button of the same name (Fig. 7.20). The advantage of the Editor is that it uses spin button controls, which make it easy to increase or decrease the parameters. If necessary, the infiltration equation can also be changed with the Editor. After finding an acceptable solution, press on the Save button to return to the Infiltration Tab page and transfer the estimated infiltration parameters to that form.

Update Shape Factors: This button, located on the bottom left of the tab page (Fig. 7.20) will be displayed only when volume balance calculations utilize surface and subsurface shape factors. Those shape factors need to be refined as part of the analysis, as their value depends on the estimated infiltration parameters. Volume balance results may change after pressing this button, in which case infiltration parameters will have to be further modified. These calculations may need to be carried out more than once, and need to be repeated if the roughness parameter changes during the analysis.

Final Infiltration: Observations and predictions are displayed graphically. In principle, the solution is found by minimizing the sums-of-squares of the differences. Although mathematical optimization can be used to solve this type of problem, it was not implemented in WinSRFR, for two reasons. First, with this type of problem, the optimal point is not well defined and can cause convergence problems. Second, and most importantly, all solutions are uncertain because of the inherent variability of infiltration and the uncertainty of the measurements.

Roughness This tab page (Fig. 7.21) will only be displayed if the **Flow Depth Hydrographs** control in the Start page is checked. The associated volume balance calculations check-

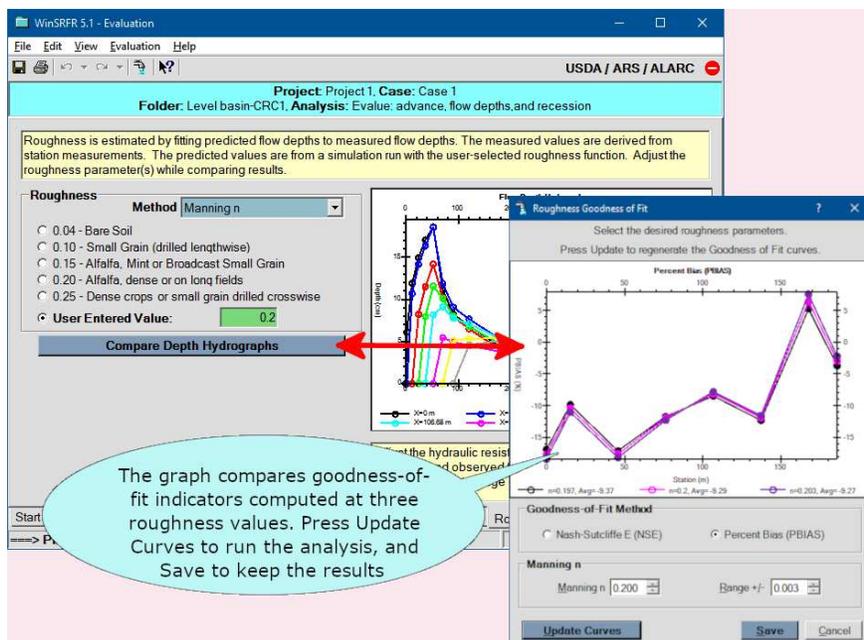


Figure 7.21: EVALUE analysis: Roughness tab

box does not need to be checked to conduct a hydraulic resistance analysis. The tab page consists of three panes, two of which are graphical outputs. The roughness parameter is calibrated by comparing simulated with measured flow depth data. Pressing the Compare Depth Hydrographs button will display the Roughness parameter calibration tool. The analysis is conducted by running three unsteady flow simulations, using the range of resistance values defined with the input boxes in the Manning n pane. Results from each simulation are compiled by the application and used to evaluate the agreement between measured and predicted values, using a user-selected goodness-of-fit indicator. The available choices are the Nash-Sutcliffe Efficiency (NSE) (Nash and Sutcliffe, 1970) and the Percent Bias (PB) (Gupta et al., 1999) indicators. The NSE indicator equals unity when the observed and predicted values are in perfect agreement, and are less than one otherwise. Percent bias measures the average tendency of a model to over- or under-predict the observations which is indicated, respectively, by negative and positive values (therefore, with zero indicating perfect agreement). Simulations can be repeated using a different range of the resistance parameter. The objective then is to find a resistance value than will maximize the level of agreement. The average indicator value for each n value tested is displayed at the bottom of the form. Saving the computed results will update the resistance parameter for the scenario, and will summarize the analysis by displaying the measured and simulated flow depths and the resulting performance indicators.

Verify: As with other estimation methods, the final step in the analysis to verify the estimated function and summarize the results. Error messages will be issued if the verification cannot be completed due to incomplete or inconsistent data. Intermediate verifications will be required if the analysis includes estimates of roughness and of

depth-dependent infiltration parameters.

Infiltration (Estimation of flow-depth dependent infiltration parameters): This functionality is accessed by pressing the Show Depth-Dependent Functions button. This button is enabled after conducting a successful verification simulation with any empirical infiltration function. In principle, users can proceed to estimate flow-depth dependent infiltration parameters without first calibrating the roughness parameter, i.e., will not follow the red arrows of Fig. 7.14 but such an approach is not recommended. Pressing the Show Depth-Dependent Functions button changes the options displayed by the Wetted Perimeter (in the case of furrows) and Infiltration Equation drop down controls. With borders, the only choice is the Green-Ampt equation. With furrows, the Wetted Perimeter control will display the Local Wetted Perimeter option only and two choices for the Infiltration equation, Modified Kostiakov and Warrick-Green-Ampt.

The rest of the estimation process is the same as for standard infiltration functions. The graph on the right-hand side of the Infiltration tab page displays the measured and predicted infiltration volumes at the selected volume balance calculation times. The analysis seeks to find parameters that will mostly closely match the measured and predicted infiltration volumes. Parameter values are adjusted directly with the input boxes in the tab page, or with the Infiltration Function Editor. If the hydraulic resistance parameter was calibrated from field data, it should not require additional adjustments when changing from a standard to a depth-dependent infiltration function. If a standard function needs to be recalculated, press the Show Standard Functions to restore the corresponding controls in the Infiltration tab page.

7.4.3 Outputs

Outputs generated by the analysis are summarized in Table 7.6. Note that the EVALUE analysis produces a graphical report of the volume balance calculation errors, which are determined by comparing volumes determined from field measurements and simulated volumes. In general, relative errors will be large at short times but will decrease later in the irrigation. Relative errors that increase with time are an indication of problems with the calculations, for example, failing to update the shape factors.

7.4.4 Examples

The scenarios in the *EVALUE examples.srfr* file are organized in two case folders, each with two Event Analysis folders. The first group applies the EVALUE method to free draining furrows and the second to basins.

7.4.4.1 Benson Furrow

The first Event folder, *Benson 2-5-2*, contains data for the same scenario analyzed in the Merriam-Keller example file, Benson Irrigation 2, Group 2 Furrow 5 (Elliott, 1980), except that flow depths were added to the data set. In the *Clean* scenario, analysis tables and graphs

Table 7.6: Outputs of the EVALUE volume balance analysis

Output Tab	Description
Input Summary	Summary of inputs
Hydraulic Summary	Combination graph showing measured and predicted advance-recession times, runoff data (if applicable), and predicted final infiltration
Volume Balance	Graphical summary of volume balance calculation errors
Infiltration Function	Estimated infiltration function as a function of time. Note that the left vertical axis represents A_z while the right represents A_z/W (borders) or A_z/FS (furrows).
Performance Summary	Efficiency and uniformity indicators
Parameters and Goodness-of-Fit	Parameter values and goodness-of fit statistics computed from observations and simulation results

do not contain data, shape factors have not been calculated, and the infiltration parameters and Manning n are set to default values. Use the Clean scenario to find a solution on your own, and also to examine intermediate outputs during the analysis. The analysis has been completed in the scenario labeled Final.

Inspect first the the [Field Measurements](#) section in the **Start** tab page. Runoff rate, recession times, and flow depths are optional measurements available for this analysis, hence those data checkboxes are checked. Examine next the data to assess their use in volume balance analyses. With these data Eq. (B.1) can be applied up to the final measured runoff time⁴. The flow depth values cannot be used to determine V_y because they were measured at only a few locations and times. The checkboxes below the label [Use for VB](#) indicate that only runoff data will be included in the volume balance analysis. Other data will be used for verification and calibration of the roughness parameter.

The next step in the analysis is to select the volume balance calculation times. The Benson data set includes advance measurements every 25 m and those application can make those selections (by pressing the [Calculation Times](#) button), or the user can specify them by editing the first column in the [Volume Balance Table](#). Note that volume balance can be calculated at all available advance times (25 in this example), but the application is programmed to select 12 or less times in total. This is a reasonable number of calculation times if the data does not show any anomalies or irregularities. If the advance time and runoff measurements are very erratic, additional calculation times can be added manually. The

⁴Note in the [Inflow/Runoff](#) tab that the [Partial Hydrograph](#) checkbox is also checked, to indicate that runoff measurements are incomplete.

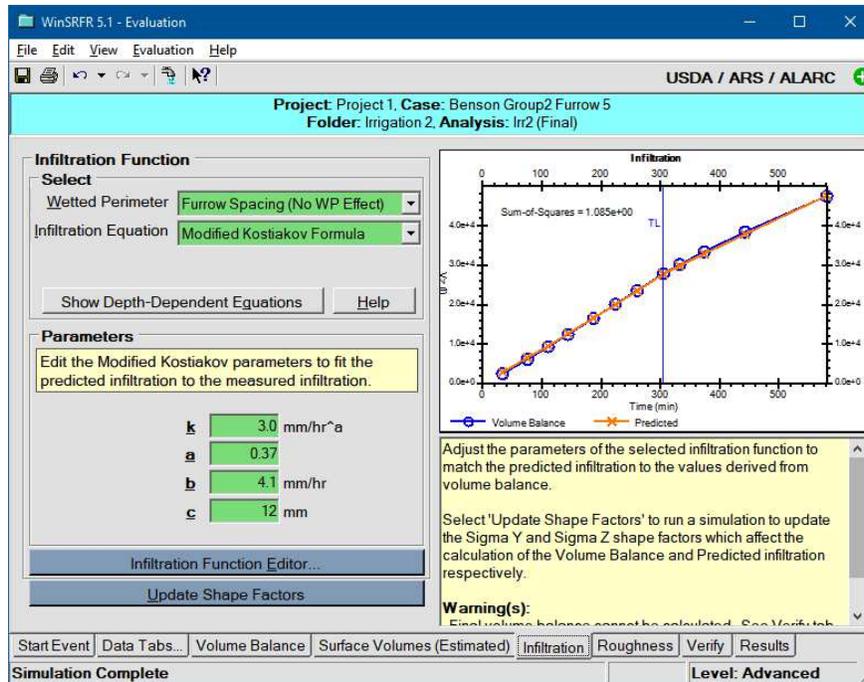


Figure 7.22: Comparison of volume balance-calculated and predicted infiltration with EVALUE.

graph in the tab page summarizes the advance time, recession time, inflow, and runoff measurements and overlays the selected volume balance calculation times as horizontal blue lines.

Review the calculated surface volumes using the **Surface Volumes (Estimated)** tab. The estimated surface volumes (Eq. B.2) depend on the unknown Manning n and the shape factors σ_y which vary with each calculation time. Use initially the recommended n value for furrows, 0.04.

Estimate the empirical infiltration parameters with the **Infiltration** tab, using the process described in the previous section. The recommended infiltration modeling approach is to use the furrow spacing option and the Modified Kostiakov equation, but other choices are available. Use judgment when fitting the infiltration function. With this example, the measured and predicted infiltration volumes can be closely matched (Fig. 7.22), even with inaccurate initial estimate for the Manning n , due to the high quality of the data and apparent uniformity of field conditions. Fitting the function will be more difficult with erratic data. If the data is erratic, give greater weight to measurements that are more reliable. In general, infiltration measurements early during the advance phase tend to be erratic because of the rapid growth of the surface stream, which is difficult to evaluate. Infiltration measurements tend to be more reliable during the storage phase of an irrigation event, as the surface volume stabilizes (in free-draining systems) or grows very slowly (in blocked systems).

After finding a reasonable set of parameters, use the estimated parameters to conduct an unsteady simulation (**Verify** tab). The application will issue an overflow warning - the

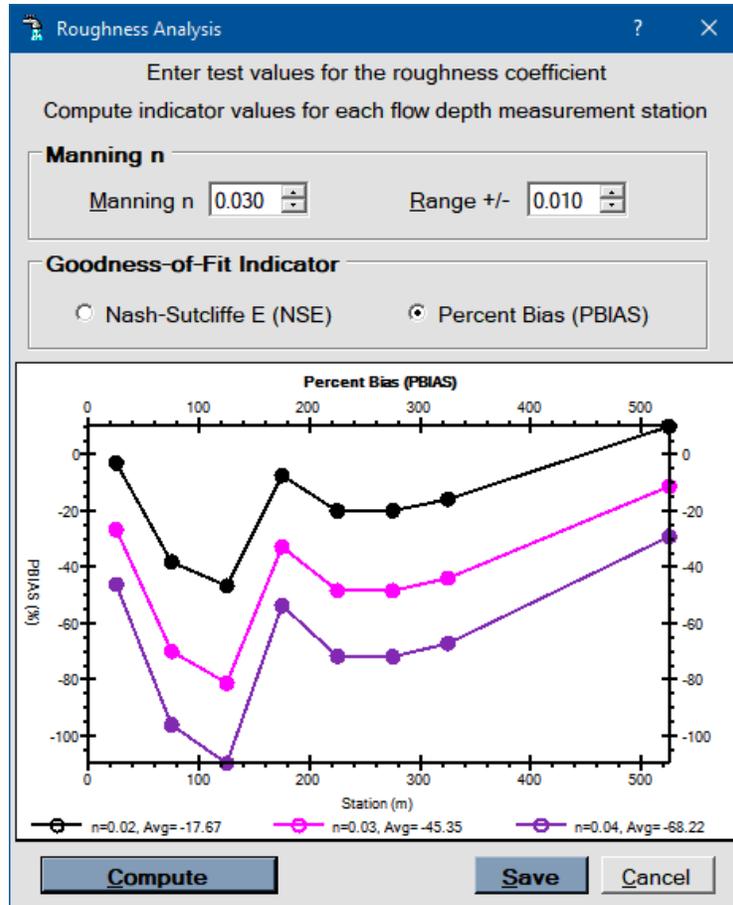


Figure 7.23: Estimation of the roughness coefficient using the PBIAS goodness-of-fit indicator.

simulated flow depths exceed the measured furrow maximum depth. This is an indication that the n value assumed in this initial part of the analysis is excessive.

Use now the **Roughness** tab to calibrate the Manning n coefficient, using the process described in Section 7.4.2-Roughness. Figure 7.23 illustrates calibration results computed with the PBIAS indicator, and with the Manning n centered at 0.030 and the range defined as 0.01 (i.e., with $n = 0.02, 0.03$ and 0.04). This very wide range was selected to illustrate the resulting large differences in PBIAS values. Indicator values computed for different stations can vary widely, as shown in the graph, due to systematic field measurement errors (e.g., survey errors). Results suggest that a value of Manning n less than 0.02 can force the average PBIAS closer to zero, and in fact, for this example the average PBIAS is minimized with $n = 0.015$.

Using this new value of the Manning n , return to the infiltration tab and re-estimate the infiltration parameters. Running an unsteady simulation with the new parameter estimates will eliminate the overflow warning, but the application will generate a different warning, indicating that it cannot compute a final volume balance because of the limitations of the

data. This is provided for informational purposes only. Compare the simulation results with the available measurements, using the **Hydraulic Summary Output** and **Parameters & Goodness of Fit** tabs. Since the measured and predicted infiltration volumes match very well, the advance times, runoff rates, and recession times are also in close agreement. Note that the recession times provide the only independent measure of goodness-of-fit, as those data were not used in the volume balance analysis.

Open and execute the *Irr2 (Final)* scenario and compare the infiltration function with the one you estimated using the *Irr2 (Clean)* scenario. The infiltration functions should be similar, even if the parameters are not. It should be clear then that more important than a particular set of parameters, is to develop a broad understanding of the infiltration and resistance processes for a particular field. For example, evaluation results may provide us with a reliable measure of the steady infiltration rate, even if cumulative infiltration with time cannot be properly evaluated. As stated in Section 2.2, the spatial and temporal variability of infiltration and hydraulic roughness make all estimation results uncertain. That uncertainty can only be reduced by analyzing multiple irrigation evaluation data sets.

Verify the estimation results generated with the *Irr2(Clean)* scenario. This action will enable the procedures for estimating parameters of flow-depth dependent infiltration equations. As previously indicated, this type of analysis is recommended only when supported by measured flow depths, and therefore, a field-calibrated resistance coefficient. Press the **Show-Depth Dependent Equations** button. The **Wetted Perimeter** drop-down box in the Infiltration tab will select the **Local Wetted Perimeter** option. Select then the Warrick-Green-Ampt equation. There are two difficulties with the estimation of the corresponding parameters. One is that there are four parameters to deal with, which have physical significance. The other is that, as explained in Section 5.4.2.2, the WGA equation represents only porous-media flow. Infiltration in irrigated soils is partly porous media flow, and partly flow through cracks and macropores. Such effects are often embedded in the parameters of empirical infiltration equations, and therefore overlooked. With the WGA equation, macropore effects must be simulated with the empirical macropore constant c . Macropore effects can be substantial at short times. For this example, estimates for the initial and saturated water contents are available from field measurements reported by Elliott (1980) and a reasonable estimate for the wetting front pressure head can be derived from the reported soil texture (clay loam) and pedotransfer functions. Use the values provided in the *Irr2(Clean)* scenario to estimate the hydraulic conductivity and the macropore infiltration constant. See Bautista and Schlegel (2017b) and Guzmán-Rojo et al. (2019) for additional details on the estimation of parameters of the Warrick-Green-Ampt equation.

7.4.4.2 CRC Basins

This folder contains two scenarios, labeled CRC1 and CRC4, which were obtained from two basins evaluated on the same field. They are part of a data set reported by Bautista et al. (2009a). The data sets includes inflow rate with time, and advance, and recession times at different distances. In addition, it contains detailed flow depth measurements that can be used to determine surface volumes. The basins are of nearly the same length, but differ in

Event Analysis (Field Evaluation)

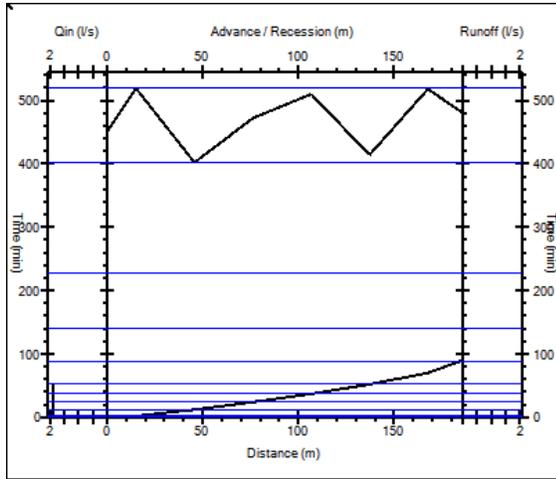


Figure 7.24: Volume balance calculation times for scenario CRC1.

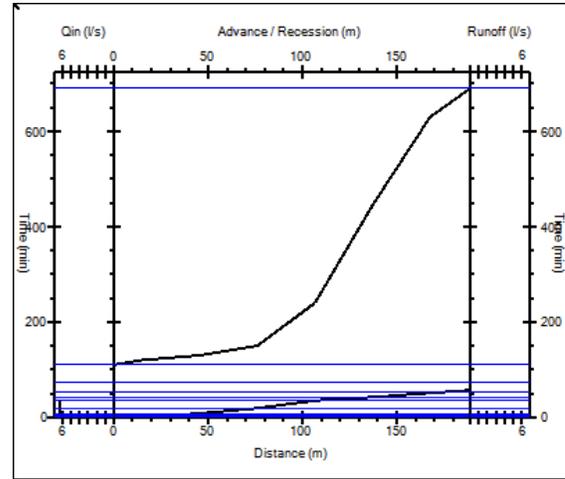


Figure 7.25: Volume balance calculation times for scenario CRC4.

the bottom slope, which is near zero for CRC1 and close to 0.1% for CRC4. They also differ in the inflow rate that was applied. The inflow rate was reported on a per unit width basis as 1.9 l/s/m for CRC1 and 6.3 l/s/m for CRC4.

Figure 7.24 illustrates the volume balance calculation times selected by the application for the scenario CRC1. Note that a post-irrigated volume balance can be calculated based on the available data. In addition, the application proposes calculating volume balance at each of the advance times, and several times between final advance and the beginning of recession. The corresponding selections for the scenario CRC4 are shown in Fig. 7.25. The difficulty with this example is that recession begins only a short time after final advance while final recession happens much later. The application selects the volume balance calculation times using the same rules with both examples, but those rules work better (times are more widely spread) for the first example than for the second. For CRC4, calculation times need to be specified manually after the final advance. Obvious candidates are the measured recession times. Those times have been selected in the CRC4 (2) scenario. Compare the **Hydraulic Summary** tab for that scenario and compare it with Fig. 7.24.

Figures 7.26 and 7.27 illustrate the water surface elevation profiles computed for scenarios CRC1 and CRC4 (2), which are displayed in the **Surface Volumes (Measured)** tab page. In both cases, the profiles evolve smoothly with time, showing how the surface volume grows up to cutoff time, and decreases thereafter. Use the menu commands *View/Select Graph* to inspect each curve individually and see the progression of the profiles with time. The computed profiles may not always evolve as smoothly as shown in the figures.

The computed infiltration volumes and fitted functions are depicted in Figs. 7.28 and 7.29. Notice that the computed infiltrated volumes do not vary smoothly with time, in particular for the CRC4 scenario. In fact, for that scenario, results show that infiltration volume increases, then decreases, then increases again after the final advance time. The

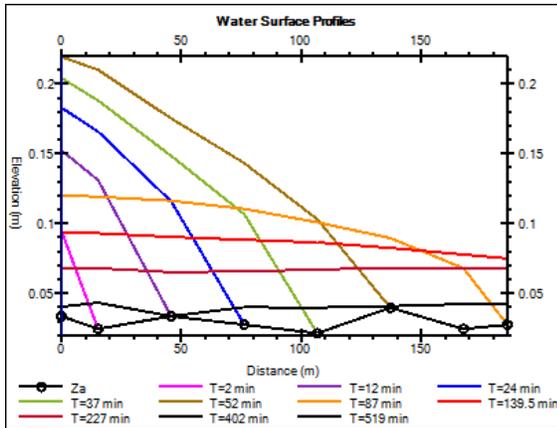


Figure 7.26: Water surface elevations calculated for scenario CRC1.

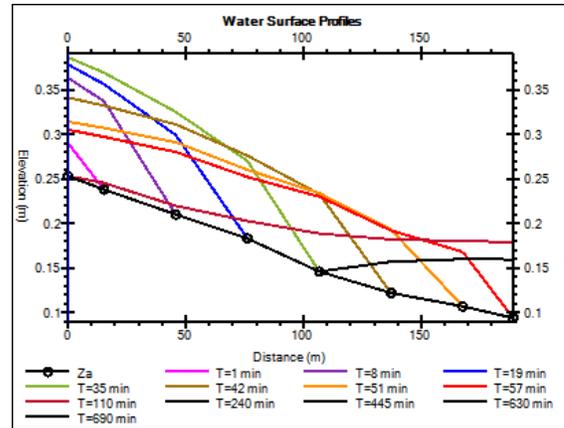


Figure 7.27: Water surface elevations calculated for scenario CRC4 (2).

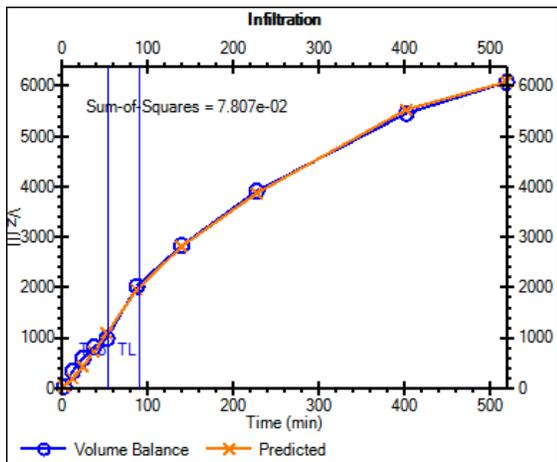


Figure 7.28: Infiltrated volumes and fitted function for scenario CRC1.

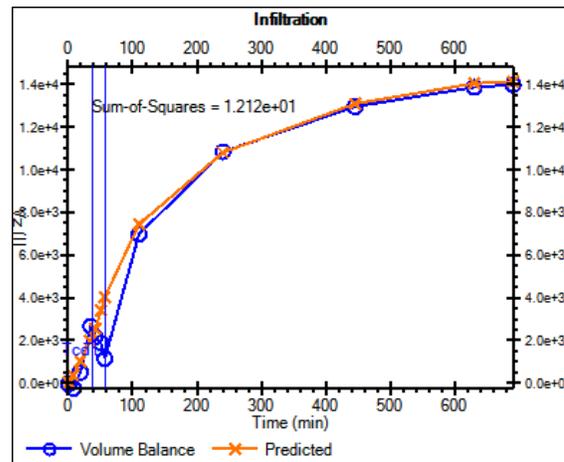


Figure 7.29: Infiltrated volumes and fitted function for scenario CRC4 (2).

application will issue a warning as it expects infiltrated volumes to always increase with time. This illustrates the uncertainty of the measured volumes at short advance times. The large inflow rate used for this test may contribute to the difficulty in obtaining accurate water depth and, therefore, volume measurements. After cutoff time and after the stream reaches the end of the field, surface volume changes more slowly and the resulting infiltration estimates are more consistent with time.

Figure 7.30 shows the Manning coefficient calibration results, as displayed in the **Roughness** tab, for the CRC1 scenario. The graph on the left summarizes the goodness-of-fit values computed at each of the depth measurement stations. The graph on the right compares measured with predicted flow depths. Only two time series are displayed in this graph, to facilitate their inspection. The first thing to note is that while the goodness-of-fit indicators appear to vary substantially among stations, measured and predicted values are in very good agreement everywhere.

Event Analysis (Field Evaluation)

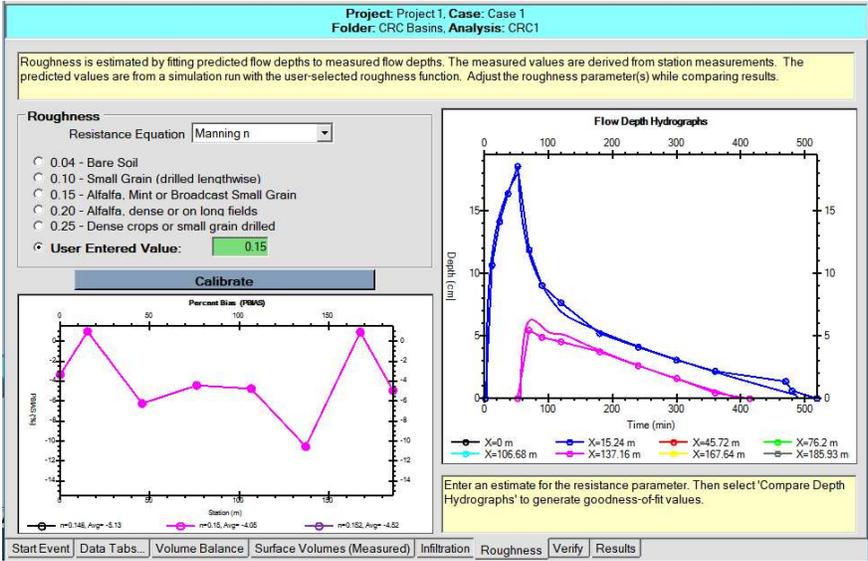


Figure 7.30: Estimation of the Manning n coefficient for scenario CRC1.

OPERATIONS ANALYSIS

The Operations Analysis World is used to examine the hydraulic performance of a system of known physical dimensions as a function of inflow rate and cutoff time. It can be used to optimize the operation of a system, or as part of a design analysis, to examine the sensitivity of a proposed system to variations in inflow rate. The latter use will be illustrated in the next chapter. The procedures in this World use a subset of configuration options available for simulation, which are summarized next.

8.1 Inputs

8.1.1 Start

Like other Worlds, an Operations Analysis begins by specifying the System Type and the Required Depth. The methods in this World can be applied to furrows and borders, either with an open or closed downstream end. The System Type limits the set of options that can be displayed in the System Geometry, Soil/Crop Properties, and Inflow/Runoff tabs. In addition, the System Type limits the Contour Types offered for the analysis (Fig. 8.1):

Inflow Rate and Cutoff time for the known (Border/Furrow set) Width: This default option applies to any system type. As the name indicates, this analysis uses inflow rate and cutoff time as the decision variables.

Furrows per Set and Cutoff Time for the Known Inflow Rate: This alternative is available for furrows only. Use this option when the objective is to recommend a furrow set size (and associated cutoff time), based on the available inflow rate and specified field length.

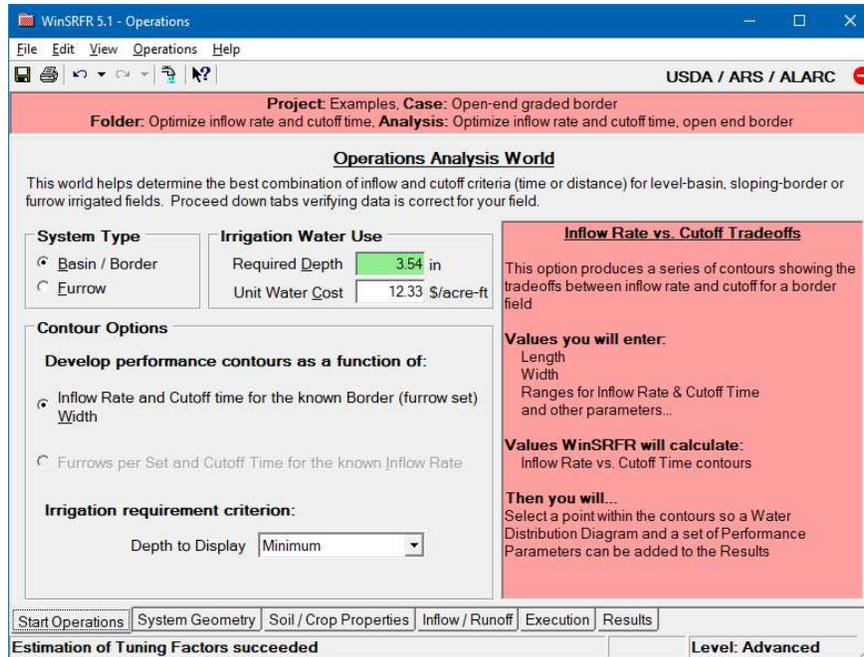


Figure 8.1: Operations Analysis: Start tab page

In the following paragraphs, these two alternatives will be identified as Option 1 and 2, respectively.

Ultimately, an Operational Analysis aims to identify solutions that satisfy the irrigation requirement. Those solutions define the potential application efficiency of the system under the range of inflow rates considered in the analysis. Two options (Irrigation Requirement Criterion) are available for this purpose, which are selectable with the **Depth to Display** drop-down control:

Minimum: This default option identifies solutions for which the minimum depth in the final infiltration distribution is equal to the irrigation requirement ($D_{min} = D_{req}$). With those solutions, the irrigation requirement is met everywhere along the field length and the computed application efficiency represents the potential application efficiency of the minimum PAE_{min} .

Low-quarter: This option identifies solutions for which the low-quarter infiltrated depth is equal to the irrigation requirement ($D_{lq} = D_{req}$). D_{lq} is the average depth for the 25% lower percentile of the final infiltration distribution. Those solutions produce a water deficit in a small part of the field, with the computed application efficiency representing the potential application efficiency of the low-quarter PAE_{lq} .

For a given set of conditions, the D_{min} criterion will increase water losses and, therefore, lower application efficiency in comparison with the D_{lq} criterion. Use of D_{lq} is recommended when the water supply is limited and/or costly, the economic impact of the water deficits are limited, and when trying to minimize water losses and the environmental impact of irrigation.

8.1.2 Geometry

Most of the geometry options available for simulation are also available for Operations Analysis. Exceptions are the following:

- The analysis only considers the case of a uniform bottom slope (specified with the Slope, Average from Slope Table, or Average from Elevation Table bottom description options).
- When analyzing using furrow set size and cutoff time for a given inflow rate, the number of furrows per set is an output of the analysis and cannot be specified in the corresponding input box. After selecting a solution point, the box will display the Number of furrows for that solution point.

8.1.3 Inflow/Runoff

Most operations analyses assume a constant inflow rate. As a result:

- Inflow can be specified with a Standard Hydrograph only, with time-based cutoff.
- With furrows, the analysis can consider systems with inflow cutback, where the cutback is specified as a function of time (advance distance-based cutback not available).
- If the analysis uses Option 1, then the Inflow Rate and Cutoff Time input boxes are non-editable. Those boxes will display the inflow rate cutoff time of the selected solution point. If Option 2 is used instead, then the Number per Set and the Cutoff Time input boxes are non-editable, but will display the selected solution point.

8.1.4 Soil/Crop Properties

The volume balance procedures used to compute the contour grid points (see below) require infiltration to be a continuous function of opportunity time only. This limits the choices for modeling infiltration:

- With border/basin systems, an Operations Analysis cannot be conducted in combination with the Branch, Green-Ampt or Richards infiltration equations.
- With furrows, the analysis cannot be conducted in combination with the Local Wetted Perimeter option, or with the Branch equation in combination with any wetted perimeter option.

In addition, hydraulic resistance can only be modeled with the Manning equation.

8.2 Execution

This tab (Fig. 8.2) consists of four inputs panes. The **Contouring Options** pane re-displays the analytical options shown in the **Start** tab and does not need additional explanations. Controls that are key to the analysis are located in the **Contour Configuration** and **Tuning Factors** panes.

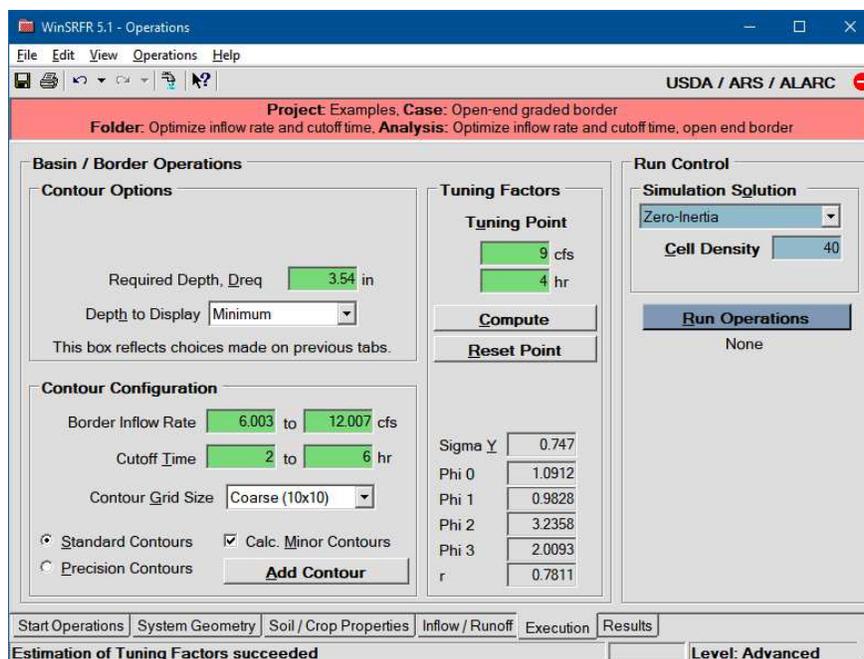


Figure 8.2: Operations Analysis: Execution tab page

8.2.1 Contour Configuration

This set of controls configures the contour region, structure, and computations.

Inflow Rate/Cutoff Time: Use these controls to specify the operational variable range to plot (the contour region). Minimum and maximum values for Inflow Rate and Cutoff Time (Option 1) or Furrows per Set and Cutoff Time (Option 2) need to be given. Generally, the range of inflow rates to plot will be dictated by the range of water supply rates available to a field. Different combinations for the minimum and maximum values for the operational variables will have to be tested in order to identify an acceptable solution region. For example, if the initially provided range of flows and times is too small, water will not reach the end of the field and contours will not be generated. Start by defining a broad range and gradually zoom into a region of interest.

Contour Grid Size: WinSRFR calculates performance results at discrete points on a rectangular grid. The contours are generated by interpolating from those points. The density of the grid can be set to Coarse (default), Medium, and Fine with the Contour Grid Size drop-down control. Use the Coarse option first, when defining the contour region. Use the Medium or Fine options later, to improve the accuracy of the interpolation scheme and of the contours.

Standard vs. Precision Contours: These option buttons select the interpolation algorithm used to develop the contours. Standard (default) selects a low-order interpolation scheme while Precision selects a high-order scheme. Use the Precision option to smooth jagged contours produced with the standard option. Since Precision Contours

increase the computational time by an order of magnitude, they should be used only after testing first the use of a Fine Contour Grid.

Calc. Minor Contours: This option calculates contours at smaller intervals. If this option is checked after contours are displayed, recompute the contours.

Add Contour Overlay: An overlay combines two or more sets of performance contours so that the relationship between those indicators can be more easily examined. Only one overlay can be generated, which is configured with the Add Contour Overlay button. The selection form is self-explanatory. The overlay can be modified without recomputing the contours, but the graphical results must be refreshed manually by pressing F5.

8.2.2 Tuning Factors

WinSRFR generates performance contours using volume balance calculations. Those calculations use shape factors to describe the surface and subsurface profiles at different stages of the irrigation event. The shape factors need to be calibrated to better match volume balance results to unsteady flow predictions. The calibration uses unsteady simulation results from a single point in the solution region.

Tuning Point: The application automatically sets the tuning point to the middle of the contour region based on the minimum/maximum values for the decision variables. The tuning point coordinates (e.g., a flow rate and cutoff time combination if using Option 1) are shown in the corresponding text input boxes. The tuning point can be set manually when tuning computations fail, as is explained next.

Compute Tuning Factors: Press this button to compute the tuning factors. If the calibration computations are successful, the application will display the updated values in the boxes labeled PHI0-PHI3. Otherwise, the application will display an error message. The calibration will fail if the tuning point application depth is less than Dreq, or if the stream cannot reach the end of the field. If the Tuning Factor calculations fail, the recommended approach is to increase the maximum value for Inflow Rate and/or Cutoff Time. This will shift the calibration point upwards and increase the applied depth associated with that point. Alternatively, the tuning point can be set manually. Since the tuning calculations are specific to a set of inputs, they must be recomputed if any input is modified. Additional comments on the quality of the calibration procedure are provided later in this chapter.

If an acceptable tuning point cannot be readily found, generate the performance contours with the default tuning factors and use these results as a guide for selecting acceptable coordinates. Since the calibrated volume balance results are most accurate near the tuning point, move the point close to the dotted line that represents solutions that satisfy the irrigation requirement (i.e., the PAEmin or PAElq line). It is always

advisable to move the tuning point close to the potential application efficiency line, even if the point is accepted by the application. Note also that the application will issue a warning when the volume balance calculations produce a value for the power advance exponent less than 0.5, which indicates that water advances relatively slowly with the tuning point. The recommendation is to use a point with a larger inflow rate.

Tuning Factors: These boxes display the computed values. They are displayed for informational purposes only. The Tuning Factors are used differently depending on the system type. In general, *Phi0* matches the advance time to the end of the field and *Phi1* matches the downstream recession time. The infiltrated volumes are then matched using *Phi2* & *Phi3*. The calibration of *Phi0* requires an initial estimate for the surface shape factor *SIGMAY* (σ_y). That estimate is generated by the program and displayed above *PHI0*.

Reset Point: Automatic selection of the Tuning Point is disabled after those values are entered manually. Pressing this button resets the automatic calculation of the solution point.

8.2.3 Run Control

Simulation Solution Model: These options were explained in Section 6.1. The simulation engine is used to calibrate the tuning point and to verify the solution point. For most analyses, the user will not have to edit these controls.

Run Operations Analysis: After completing the tuning process, press this button to compute the contours. Messages indicating the progress of the calculations will be displayed at the bottom of the Execution tab. Warning/error messages may be displayed at the end of the calculations, generally to alert the user to variable combinations in the contour region that do not satisfy the problem's requirements. The contours will not be displayed until those messages are closed.

8.3 Outputs

The Operations Analysis output consist of performance indicators displayed in several Results tab pages. The performance indicators are defined in the Terminology section. Outputs differ depending on the selected Infiltration Depth criterion, as indicated by variables in parentheses in Table 8.1. The interpretation of the performance contours is discussed in the Examples section of this chapter.

NOTE

Use the *Edit/User Preferences* command to customize the performance contour color scheme. After making the desired changes, press F5 from the Operations Analysis window to update the display.

Table 8.1: Operations Analysis: Summary of outputs

Tab page	Description
Input Summary	Tabular summary of inputs
AE	Contour graph of the application efficiency
DUmin (or DUlq)	Contour graph of the distribution uniformity of the minimum (or the low-quarter)
ADmin (or ADlq)	(or Contour graph of the adequacy of the minimum (or the low-quarter)
RO	Contour graph of the runoff fraction
DP	Contour graph of the deep percolation fraction
Dapp	Contour graph of the applied depth
Dmin (or Dlq)	Contour graph of the minimum (low-quarter) infiltrated depth
Txa	Contour graph of the final advance time
XR	Contour graph of the advance ratio
Cost	Contour graph of the cost of the applied water
Solution	Graph of the final infiltrated profile and performance summary table for the selected solution point
Dreq = Dmin (or Dlq)	Graphical summary of solutions that satisfy the Dmin (Dlq) = Dreq depth criterion
Hydraulic Summary	Graphical comparison of volume balance and unsteady flow simulation predictions (advance, recession, inflow, outflow, final infiltration) for the selected solution point

8.3.1 Navigating the contours: the Water Distribution Diagram

The performance contours provide an overview of performance changes as a function of the operational variables. Additional details can be obtained by navigating over the contours with the cursor. The standard Windows arrow cursor will be replaced with a cross-hair cursor and display in a balloon box the coordinates of the point and its performance value.

The contour graph can be inspected with greater detail with the Water Distribution Diagram (Fig. 8.3). Display this tool by right-clicking on the contour graph and selecting the Choose Solution at this Point menu command. The diagram displays the predicted final infiltration profile and also a summary of performance measures for a selected combination of operational variables. The diagram updates its content while navigating over the contour region. To do this, move the Operations Analysis window to one side of the screen and the Water Distribution Diagram to the other so that the two windows overlap as little as

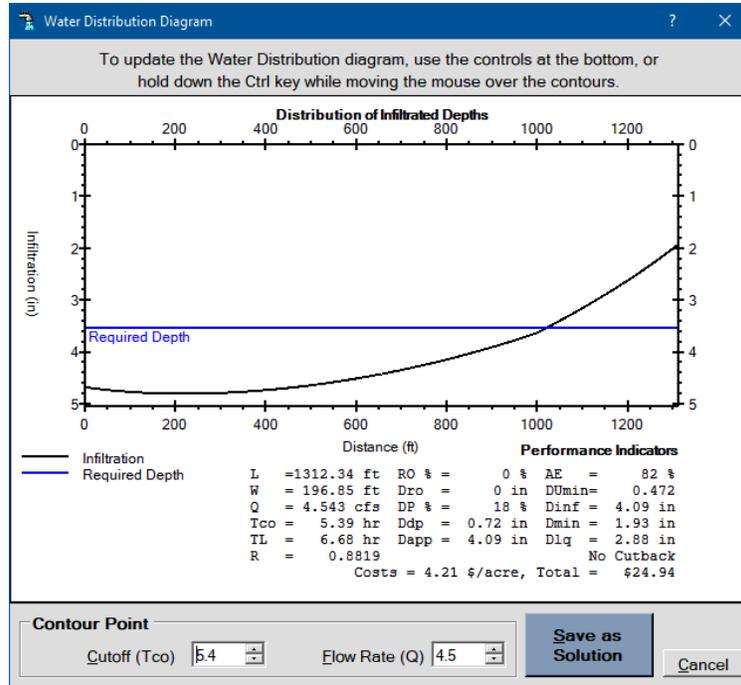


Figure 8.3: The Water Distribution Diagram

possible. Move then the cursor over the contour graph while holding down the CTRL key. The contour graph coordinates for the selected point are displayed at the bottom of the Water Distribution Diagram window, in the Contour Point box. Those coordinates can be set manually. After selecting a point, press the Save as Solution button. This command will update the results displayed in the Solution and Hydraulic Summary tabs. Use the latter tab to assess the quality of the results computed with volume balance in comparison with unsteady simulation at the solution point.

8.3.2 Assessing the accuracy of volume balance results

Volume balance calculations and the resulting contour information are reasonably accurate in comparison with results computed with unsteady flow simulation over a limited range of the decision variables. Substantial differences between the two sets of results are an indication of a poorly posed mathematical problem, which has implications for how the system behaves physically. Under a range of conditions, results will be sensitive not only to the computational method, but also to small changes to the input variables, for example infiltration. Typically, the problem will become poorly posed when the applied volume becomes too small relative to the irrigation requirement, and/or the inflow rate becomes too small relative to the system's infiltration rate. Advance will be very slow, eventually fail to reach the end of the field, and performance will degrade very rapidly with small changes to the decision variables. The application blanks out those solution regions where the problem appears to be poorly posed, to discourage the selection of solutions in that region.

The graph in the Hydraulic Summary tab overlays the volume balance predictions (ad-

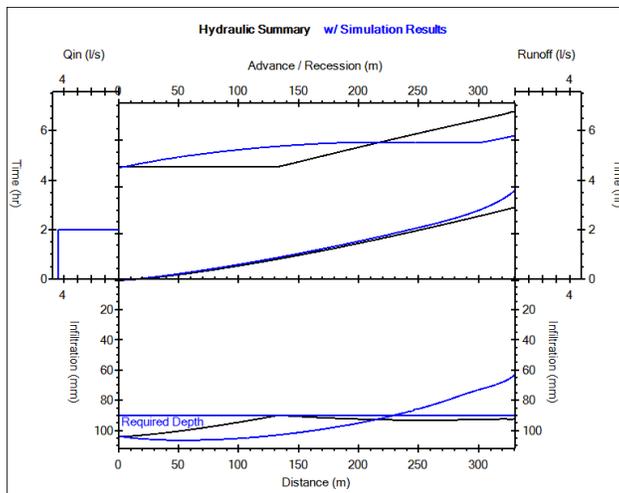


Figure 8.4: Comparison of the volume balance and unsteady simulations solutions with the Hydraulic Summary tab

vance, recession, final infiltration profile) with the corresponding unsteady simulation results for the selected solution point. An example where the two sets of results disagree is presented in Fig. 8.4 for an open-end irrigation systems. The selected depth criterion is $D_{min} = D_{req}$.

These results can be used to adjust the solution point selection, in order to better satisfy the requirements and constraints of the problem. However, because of the uncertainty of infiltration and hydraulic resistance, a more important reason for comparing volume balance and unsteady simulation results for different combinations of Inflow Rate and Cutoff Time is to identify conditions under which the problem is becoming poorly posed. Those solutions should be avoided or, at least, subjected to extensive sensitivity analyses.

8.4 Examples

Two operational analysis scenarios are presented in the Operations Analysis.srfr file. These scenarios illustrate the use of the two analytical options discussed in the introduction to this chapter. They need to be executed by pressing first the Estimate Tuning Factors button and then the Run Operations Analysis button in the Execution tab.

8.4.1 Graded border: optimize the inflow rate and cutoff time

This case folder contains one operations analysis scenario (Analysis 1) and five simulation scenarios. The simulation scenarios test the sensitivity of the proposed solution. Analysis 1 examines a 1312 ft long \times 197 ft wide (400 m \times 60 m) border, with a slope of 0.002. The required application depth is 3.54 in (90 mm). The border has a Manning roughness of $n = 0.15$ and infiltration is described with the NRCS 0.6 Infiltration Family. Examine the corresponding infiltration depth vs. time curve, shown in the Soil/Crop Properties Tab,

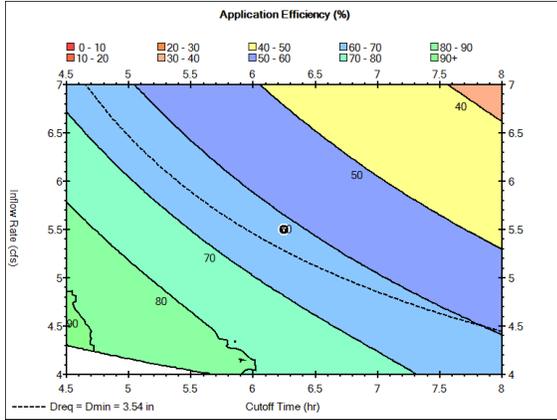


Figure 8.5: Operations analysis: application efficiency contours

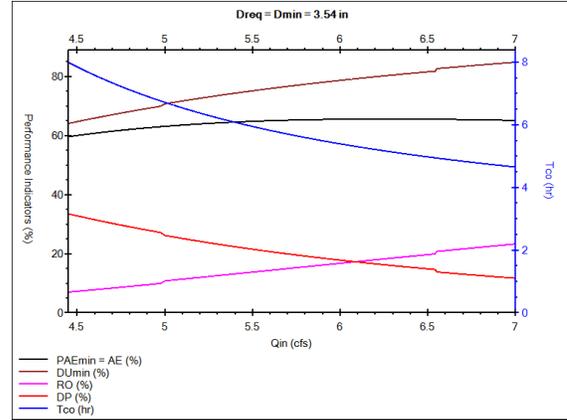


Figure 8.6: Operations analysis: performance for solutions satisfying $Ddq = Dreq$

and note that the opportunity time needed to infiltrate the irrigation requirement (τ_{req}) is 3.95 h. The maximum available inflow rate is 7 cfs (198 l/s) but the supply rate can be sometimes as low as 4.5 cfs (127 l/s). The analysis aims to examine the performance within the range of inflow rates available to the system, subject to $Dmin = Dreq$, and recommend a value considering both the potential application efficiency and management implications. In typical operations analyses, the available supply rates determines the range of inflow rates to study. Hence, contours were developed in the range of 4-7 cfs. The range of interest for the cutoff time generally must be defined by trial-and-error, as it depends on the irrigation requirement and the selected range of inflow rates. As will be shown below, solutions that satisfy the requirement lie in the cutoff time range of 4.5 - 8 hr.

After computing the tuning factors and executing the scenario, inspect the last of the results tabs, **Hydraulic Summary**. This tab compares outputs of the volume balance solution at the tuning point with unsteady simulation results. If the tuning is adequate, both sets of results will be in reasonable agreement.

Figure 8.5 depicts the resulting Application Efficiency contour (**AE** tab). The black dot with a T in the middle of the contour region ($Q_{in} = 6$ cfs, $T_{co} = 6$ hr) identifies the tuning point. Small values of inflow rate and cutoff time result in applied depths ($Dapp$) less than the irrigation requirement, and consequently, large values of AE but low values of $ADmin$ (see the **ADmin** tab). As both Q_{in} and T_{co} , increase, the irrigation requirement is eventually satisfied. The dotted line crossing through, mostly, the 60-70% AE contour is the locus of point for which $Dmin = Dreq$, i.e. the potential application efficiency of the minimum. This line was centered in the graph by adjusting the contouring range for the cutoff time by trial-and-error, as was discussed earlier. For this example, $PAEmin$ cannot exceed $\sim 66\%$. A $PAEmin$ of this magnitude is not unusual with free-draining systems. Solutions to the right of and above the dotted line result in minimum infiltration depths in excess of the irrigation requirement and low AE values.

Use the **Water Distribution Diagram** to examine the behavior of the infiltration profile throughout the AE contouring region, and in particular along the $PAEmin$ line. Pertinent water distribution measures such as Dro , $Dinf$, $Dmin$, and Dlq are updated in the Water Distribution Diagram while navigating through the solution region. Review also other performance indicator tabs.

Solutions satisfying the irrigation requirement can be easily inspected with the **Dmin = Dreq** tab (Fig. 8.6). This tab displays a combined graph of $PAEmin$, DP , RO , $DUmin$ (left vertical axis), and Tco (right vertical axis) as a function of Qin . Note that $DUmin$ is typically reported as a fraction in the surface irrigation literature but here it is displayed as a percentage. Navigate this graph with the cursor to display a performance summary for the particular flow rate. The Water Distribution Diagram can be used also in combination with this graph. For the example, $PAEmin$ is 65-66% or slightly greater in the range 5.5-7.5 cfs. Therefore, the system can be operated at nearly $PAEmin$ with a relatively wide range of inflow rates as long as the cutoff time and applied volume are carefully controlled. Evidently, AE can be increased by allowing some deficit. Of particular interest is the point where runoff and deep percolation losses are the same (i.e., where the RO and DP curves cross), approximately 6.1 cfs. Operating the system with this inflow rate is desirable because it allows the losses to shift relative to each other when infiltration and/or resistance conditions differ from those specified in the design, thus reducing the impact to application efficiency. The robustness of this flow rate will be demonstrated later.

System robustness is just one consideration involved in recommending a particular flow rate. Another consideration is the duration of irrigation sets, and how that affects the time available to irrigate the entire farm and the management of labor. The required cutoff time for an inflow rate of 6.1 is 5.3 hr. The set duration can be reduced by 0.7 hr if irrigating at the maximum available inflow rate 7 cfs but labor management is simplified if changing sets on the hour. Thus, a potential recommendation is a flow rate of 6.5 cfs, for which the cutoff time is 5 hr. Use the Water Distribution Diagram to select this combination as the solution point. With this inflow rate, runoff losses are expected to slightly exceed deep percolation (19% vs 15%) while $DUmin$ is in excess of 0.8.

The simulation folder *SensitivityAnalysis* tests the proposed solution to variations in infiltration rates. The NRCS infiltration families (IF) are useful for this purpose. The tests consider IF values in the range 0.45 to 0.8 (two families smaller and two larger than the design value). This range represents a substantial variation in the long-term infiltration rate and in τ_{req} , the time needed to infiltrate the irrigation requirement with the recommended inflow rate (from approximately 5.46 when $IF = 0.45$ to 3.45 h when $IF = 0.8$)¹. Compare the computed final infiltration profiles with the **Data Comparison Tool**. A smaller IF value decreases total infiltration relative to the irrigation requirement while a larger IF increases total infiltration. Review the performance measures displayed in the indicator tab (not shown). Nearly all losses are by runoff with the 0.45 family while losses are almost entirely by deep percolation with the 0.8 family. Both larger and smaller IF values result in

¹The time needed to infiltrate τ_{req} is shown in the infiltration tab.

under-irrigation at the downstream end of the field, but the requirement is still largely met, as evidenced by both the AD_{min} and AD_{lq} indicators. For the irrigator, it is important to understand the effect of infiltration variation on the final advance time. Under the design conditions, the predicted final advance time is nearly 4 hr. This time decreases by about half an hour with $IF = 0.45$ and increases to 5 hr with $IF = 0.8$. Ultimately, application efficiency is the same under the range of infiltration conditions considered here, 65%. This demonstrates the robustness of a properly sized irrigation system.

The reader is encouraged to clone the Analysis 1 scenario, and develop an operational recommendation based on the D_{lq} irrigation requirement criterion. As indicated before, this approach will increase AE but create a small irrigation deficit.

8.4.2 Blocked-end furrow: optimize set size and cutoff time

This scenario *Analysis 2* examines the performance of a near-level (bottom slope = 0.02%), blocked-end furrow irrigation system. The operational variables, as defined in the Start tab, are furrows per set and cutoff time for a known inflow rate (Option 2). In contrast with the previous example, the selected **Depth Criteria** is D_{lq} and the **Required Depth** is 4 in (0.1 m). The furrows are 656 ft (200 m) long. The cross-section is trapezoidal with bottom width of 6 in (0.15 m) and side slope of 1.5. The field is assumed 400 furrows wide. Infiltration is modeled with the furrow spacing option and the Modified Kostikov equation, with $\tau_{req} = 3.6$ h. The Manning n is assumed equal to 0.045 while the available flow rate is 4 cfs (1795 gpm or 114 l/s). The range of values to examine for the operational variable Furrows per Set depends on the available inflow rate and the maximum unit inflow rate (identified in this document as q_{in}) recommended under the given soil conditions. In the absence of soil-specific information, the USDA publication NEH-Ch5 Furrow Irrigation (USDA-SCS, 1978) recommends q_{in} no greater than 0.11 cfs per furrow (50 gpm or 3.2 l/s) or flow velocities no greater than 0.5 ft/s (0.15 m/s). A 40 furrow set corresponds to $q_{in} = 0.1$ cfs (45 gpm). On the other hand, a 100 furrow set requires $q_{in} = 0.04$ cfs (18 gpm), which is typical of graded furrows. With these considerations in mind, the range for Furrows per Set was set to 40 - 100 furrows. As in the previous example, the range for the variable Cutoff Times (2 - 6 h) was selected by trial-and-error to include solutions that satisfy the depth criterion.

With the given range of operational variables, the default tuning point is 70 Furrows per set and 4 h for the cutoff time. Evaluate the quality of the tuning point using the Hydraulic Summary tab. The resulting AE contour graph (Fig. 8.7) shows a white area for large values of Furrows per Set. Navigate with the cursor over this area. The program displays a message indicating that advance cannot be completed with the selected solution point. A blank region in the Operations and Design contours identifies undesirable solutions. Solutions that satisfy the depth criterion are identified with a dotted line. Those solutions suggest that a PAE_{lq} of nearly 90% is achievable. The area between the dotted line ($D_{lq} = D_{req}$) and the boundary of the white region represent solutions with high AE but which do not satisfy the requirement. Solutions below the dotted line satisfy the requirement everywhere but result in increasing deep percolation losses as furrows per set decreases and/or cutoff time increases.

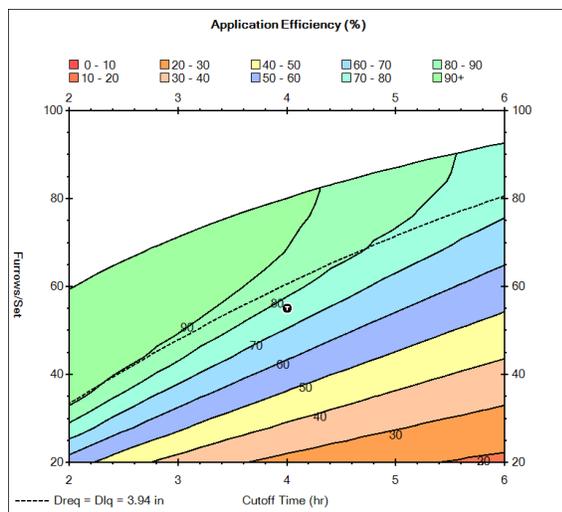


Figure 8.7: Operations analysis: application efficiency contour with cutoff time and furrow set size as decision variables

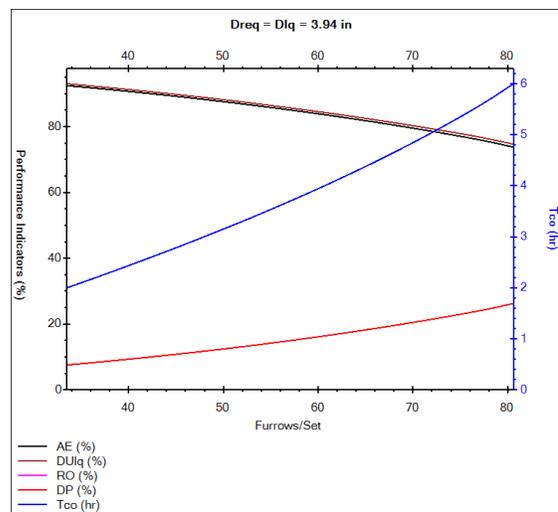


Figure 8.8: Operations analysis: solutions satisfying $Ddq = Dreq$ and the resulting performance

Inspect the **Ddq = Dreq** tab (Fig. 8.8). For irrigation systems with no runoff, PAE_{dq} and DU_{dq} are nearly the same (while $PAE_{min} \equiv DU_{min}$), and both increase as the set size decreases (i.e., as q_{in} increases). In addition to erosion, the potential for furrow overtopping is another factor that limits q_{in} and, therefore, the application efficiency that can be achieved. The program will issue a warning when the flow depth is close to the furrow depth, but does not issue a warning about erosive velocities because those conditions are soil dependent and cannot be evaluated at this time with the software. Overall, the results show that there is some flexibility in choosing a set size. If both AE and DU_{dq} are required to be between at least 85%, then the set size must be 66 furrows (6 sets) or smaller. With 400 furrows, a practical selection is 50 furrows (8 sets), for which the $q_{in} = 0.08$ cfs (36 gpm) per furrow. The potential application efficiency is 89%. An inconvenience with this selection is that the recommended cutoff time, 2.75 hr, can be difficult to manage. Rounding T_{co} to 3 h facilitates labor management but decreases the application efficiency to 82%. Nearly the same performance can be achieved with 6 sets and $T_{co} = 4$ h. This configuration requires, however, unequal furrow set sizes, 2 of 66 and 4 of 67.

The simulation folder *Sensitivity Analysis* tests the recommended operational solution (50 furrows per set, $T_{co} = 2.75$ hr) to a $\pm 25\%$ variation in the time required to infiltrate the irrigation requirement, which was imposed by varying only the steady infiltration rate parameter in the Modified Kostiakov equation. Execute the scenarios in this folder and examine them with the Data Comparison Tool. As in the first example, the impact of infiltration variations on AE is relatively small, even though the effect on the distribution uniformity (measured by either DU_{min} or DU_{dq}) is more significant. Advance times are not very different under the proposed conditions, but recession times are. With blocked systems, recession times are the best indicator of differences in infiltration conditions from those assumed in the analysis. When executing the scenario with the lowest infiltration, the

program will issue a furrow over-topping warning. Only a small part of the field is affected and only for a short time, but this potential problem needs to be considered when developing a final recommendation.

CHAPTER 9

PHYSICAL DESIGN

The Physical Design World is used to determine the dimensions of an irrigation system for a known field slope, inflow rate, infiltration, roughness characteristics, and irrigation depth requirement. The design procedures apply to furrows, borders, and basins, either with an open or closed downstream end, and to graded and level systems. As with Operations, a Physical Design analysis utilizes performance contours to identify field layouts that attain a high level of application efficiency and uniformity. Contours are computed using calibrated volume balance procedures, and are based on the same assumptions listed in the previous chapter. Likewise, the inputs and setup required for Design are very similar to those needed for Operations Analysis. The outputs are also very similar except that any feasible solutions within a design contour satisfies the irrigation requirement. In contrast, with the Operations World, only a subset of the operational combinations satisfies the irrigation requirement.

9.1 Inputs

9.1.1 Start

After selecting a System Type and defining the Required Depth (Start tab), select an analytical method with the Design Contour option buttons. The two available options are (Fig. 9.1):

Option 1. Length and Width for a Given Inflow Rate This approach is used when the inflow is fixed or when the design wants to always take advantage of the maximum available flow rate.

Option 2. Length and Inflow Rate for a Given Width This approach is most useful when the width is set by land-grading operations or when examining design relation-

ships on a per unit width basis (i.e., when examining relationships for an individual furrow or for a border/basin section 1 m or 1 ft in English units) wide.

Physical Design solutions specify the cutoff time needed to satisfy the condition $D_{min} = D_{req}$ for the given inflow rate and the selected physical layout. Operational analysis can be subsequently used to relax the selected solution to satisfy the D_{lq} criterion instead. Such an adjustment is illustrated in the Examples section.

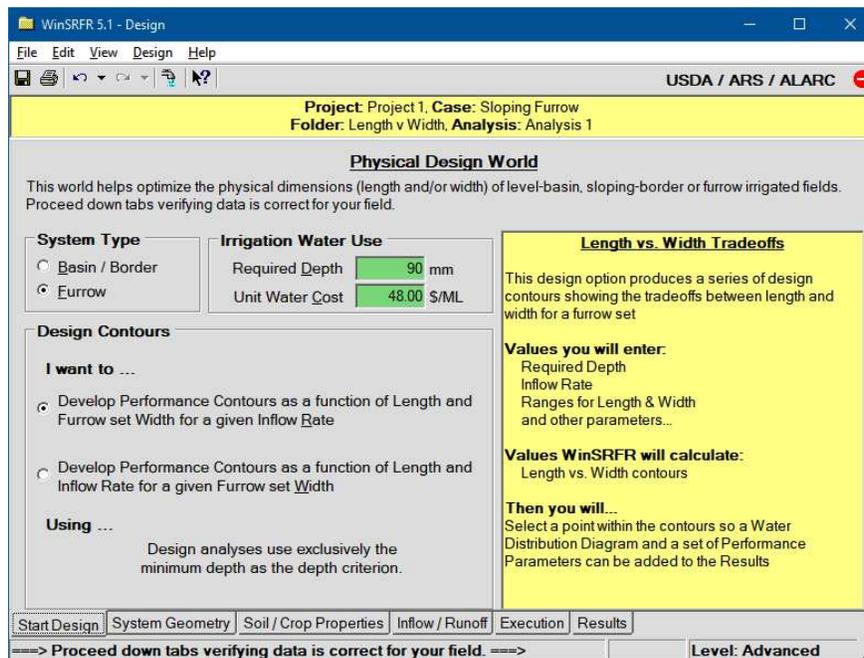


Figure 9.1: Design World Start tab

9.1.2 System Geometry, Soil/Crop Properties, Inflow/Runoff

With Design, the Length and Width (or Number of Furrows) controls in the System Geometry tab are non-editable as they are the outputs of the analysis. Since field geometric properties are assumed to be uniform (slope, cross section), all tabular inputs are disabled. The same Soil/Crop Properties options are available for Design as for Operational Analysis. Likewise, Inflow/Runoff options available for Design are the same as for Operation Analysis.

9.2 Execution

Figure 9.2 depicts the Execution tab for the Design World.

Contour Options: This section displays the analytical options of the Start tab.

Contour Configuration: Specify the contour region based on practical constraints. For example, if the total field length and width are both 400 m, enter 400 m as the maximum (border/furrow set) length and width. The minimum should be set to a practical

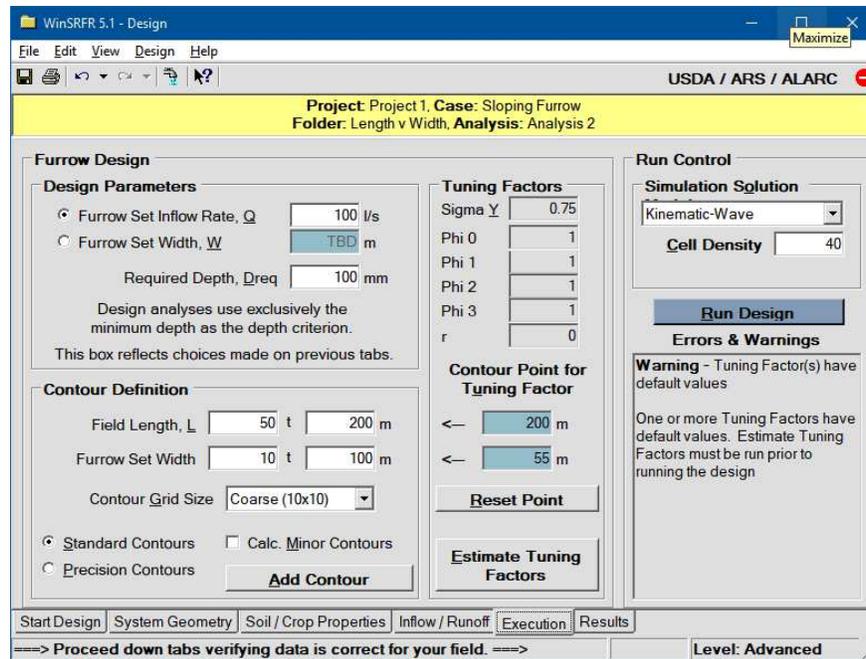


Figure 9.2: Execution tab for the Design World

value. Long fields are always desirable because they decrease the cost of the conveyance infrastructure and the cost of operation of farm equipment. Development of a contour graph for a specific problem generally will require a few iterations. An initial graph is developed based on a broad range for the decision variables, to gain an overview of the system's performance relationships. The range can be subsequently reduced to a particular region of interest.

Tuning Factors: The coordinates of the tuning point are set by the application based on the defined range for the decision variables but can be edited manually. In contrast with Operations Analysis, the initial tuning point is set by the software at the longest length and midway through the width (Option 1) or inflow rate (Option 2) range. Press the Compute button to start the calibration process. The tuning will fail if water cannot reach the end of the field. In that case, the alternatives are to redefine the contour range, which forces the application to select a new tuning point, or to set the tuning point manually. Tuning problems can be resolved by either decreasing the set size (Option 1) or by increasing the range of inflow rates to examine (Option 2). Manual editing of the tuning point coordinates will disable the automatic set up. Use the Reset button to allow the application to set the tuning point.

An adjustment to the tuning point coordinates may be required even when tuning point calculations are successful. This is because the tuning point may correspond to a point of poor performance and, therefore, of unusual values for the tuning parameters. A better location for the tuning point is near the region of high performance, which will improve the accuracy of the contours in that region.

Run Control: After completing the tuning process, press the Run Design button to compute the contours. Messages indicating the progress of the calculations will be displayed at the bottom of the Execution tab. WinSRFR will display warning/error messages if it computes solution regions that do not satisfy the $D_{min} = D_{req}$ constraint. Those messages are provided for informational purposes and can be closed to allow the program to display the contours.

9.3 Outputs

Performance contours and other outputs are displayed in tabbed pages (Table 9.1). Definitions for the performance indicators are provided in the Terminology section. Use the Water Distribution Diagram to examine individual solutions in detail.

Table 9.1: Design Analysis: Summary of outputs

Tab page	Description
Input Summary	Tabular summary of inputs
PAEmin	Contour graph of the potential application efficiency of the minimum
DUmin	Contour graph of the distribution uniformity of the minimum
ADmin	Contour graph of the adequacy of the minimum
DP	Contour graph of the deep percolation fraction
RO	Contour graph of the runoff fraction (only with free-draining systems)
Dapp	Contour graph of the applied depth
Dlq	Contour graph of the low-quarter infiltrated depth
Txa	Contour graph of the final advance time
Tco	Contour graph of the cutoff time
XR	Contour graph of the advance ratio
Solution	Graph of the final infiltrated profile and performance summary table for the selected solution point
Hydraulic Summary	Graphical comparison of volume balance and unsteady flow simulation predictions (advance, recession, inflow, outflow, final infiltration) for the selected solution point

9.4 Examples

The *Design Examples.srfr* file contains two case folders, Sloping Furrows, and Borders and Basins. The Sloping Furrow case is detailed and illustrates the use of Design World, with the support of the Operations and Simulation Worlds. Other scenarios are examined with less detail, as the goal is to illustrate the contours produced for different types of systems. For each scenario, utilize the recommended contour range and tuning point. Conduct the calibration and compute the contours. Review the quality of the calibration using the criteria outlined in the Operations Analysis section.

9.4.1 Sloping furrow

These following inputs apply to the sloping furrow scenario:

- Dreq = 90 mm
- Slope=0.002
- Furrow geometry: Spacing = 1 m, trapezoidal cross section with bottom width = 150 mm and side slope = 2
- Manning $n = 0.04$
- Infiltration is calculated with the NRCS empirical wetted perimeter option and the NRCS 0.6 infiltration family.
- Inflow rate $Q_{in} = 150$ l/s (5.3 cfs = 2378 gpm)

The field is assumed to be 600 m long and 600 m wide. The slope and cross-sectional geometry for the example are within the range of conditions for which the NRCS method is applicable. The objective is to identify a layout with high potential application efficiency and for which performance does not degrade substantially if field conditions are somewhat different from those assumed in the design.

An initial contour region can be defined by setting both the maximum length and furrow set width equal to 600 m. If the minimum acceptable furrow length is 100 m (328ft) and the maximum allowable unit inflow rate q_{in} is 3 l/s (47.6 gpm) per furrow, then the minimum length and set width for the contouring range can be set at 100 m and 50 m, respectively. With this contouring range, the application will select 600 m \times 425 m as the tuning point. This selection will produce an error message because the set is too large for the given inflow rate. An acceptable tuning point can be found by reducing the maximum length and/or set width for the contouring region, which will change the tuning point coordinates automatically, or the tuning point can be set manually as will be done here. With the length coordinate fixed at the maximum field length will not change, test set widths of 300, 200, 100, and finally 50 m. This is the value at which error messages and warnings finally disappear. Compute the contours using this tuning point.

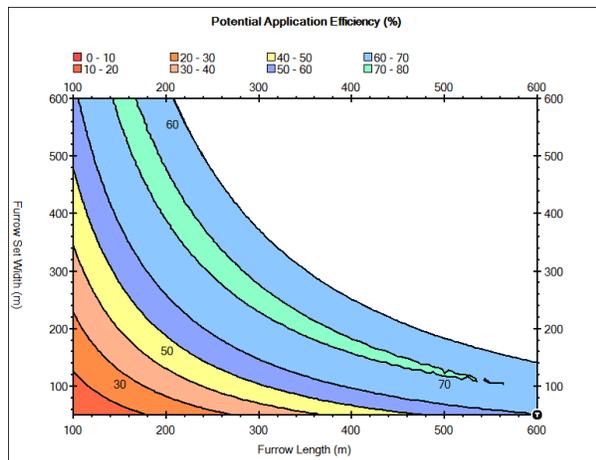


Figure 9.3: Design Analysis 1: PAEmin contours

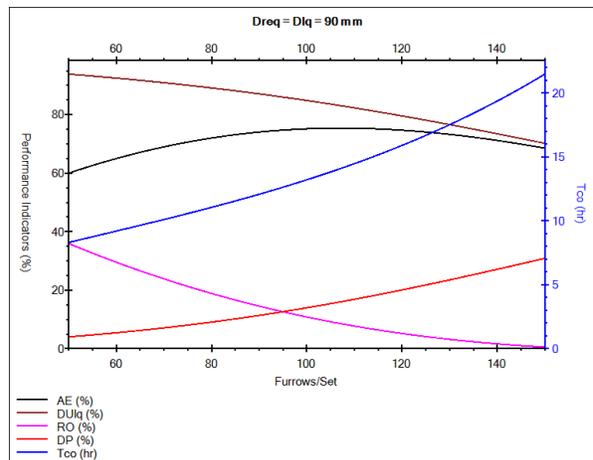


Figure 9.4: Design Analysis 1: Inflow rate adjustment

The contours (Fig. 9.3) illustrate the relationship between PAE_{min} and the design variables for a given flow rate. PAE_{min} is low with small lengths and widths because the inflow rate is too large for the set size. A PAE_{min} better than 60% (Figure 73) is attainable with a wide range of lengths and set width combinations, while a PAE_{min} of 70% can be achieved with a narrower range of combinations. Note that a 600 m \times 100 m configuration was rejected as a tuning point because advance was relatively slow. This affects the volume balance calculations and the accuracy of the contours, but does not make the point an inadequate design. Performance declines rapidly once the set size becomes too large for the given inflow rate and advance rates decline. The blank area in the plot represents set sizes for which the irrigation stream barely, or does not, reach the end of the field. It is also useful to examine the DU_{min} (distribution uniformity), RO (runoff) and DP (deep percolation) contours (not shown). Solutions near the bottom-left corner of Fig. 9.3 produce high distribution uniformity, small deep percolation losses, and large runoff losses. As the set size increases, DU_{min} and RO diminish but DP increases.

Since a long run is desirable and Fig. 9.3 suggests that high performance is achievable with the maximum field length, the analysis will continue by examining set widths in the range 50 to 120 m (164 to 394 ft), which corresponds to a range of 10 to 5 sets, with the length fixed at 600 m. The best way to compare these configurations is using Operational Analysis. Copy-and-paste the Design scenario to the **Operational Analysis World** and verify that the field length is set to 600 m. In the **Start** tab page, Contour Options, select **Furrows per set and cutoff time for the known inflow rate** (Option 2). This part of the analysis will also seek to improve the potential application efficiency, by relaxing the depth criterion. Hence, change the **Depth to Display** to Low-Quarter. In the execution tab, set the contour range from 50 to 120 for **Furrows per Set** and from 8 to 16 h for **Cutoff Time**. Compute the tuning factors with the default selection for the tuning point and then compute the contours. This analysis is summarized in the scenario *Set Width vs Cutoff Time for Length = 600 m*. The information of interest is presented in the **Dreq = Dfq** tab page (Fig. 9.4). Use the cursor or the **Water**

Distribution Diagram to inspect the details of this graph. It is desirable for the proposed system to have a high $PAElq$, but also to produce deep percolation and runoff fractions of similar magnitude, for the reasons described in the previous chapter.

For this example, losses are balanced with a 95 furrow set, which is also close to the set size of highest $PAElq$. One can get close to this configuration by dividing the field width into 6 (100 furrows) or 7 sets (85.7 furrows). Both configurations can produce a $PAElq$ better than 73% and a $DULq$ better than 0.85. The 6 set option has the advantage of equal number of furrows per set but the recommended cutoff time (13.3 hr) may be difficult to manage, even if rounding the cutoff time to 14 hr. The 7 set option requires 5 sets of 86 furrows and 2 sets of 85, but this is a minor management issue. It has the advantage of requiring essentially a 12 hr cutoff time, which facilitates labor management. Performance is nearly identical with either 85 or 86 furrows and $T_{co} = 12$ hr. Also, since the 600 m X 86 m configuration produces greater runoff than deep percolation losses, it provides greater insurance against incomplete advance if infiltration rates are greater than expected. This is the recommended set width for a 600 m length.

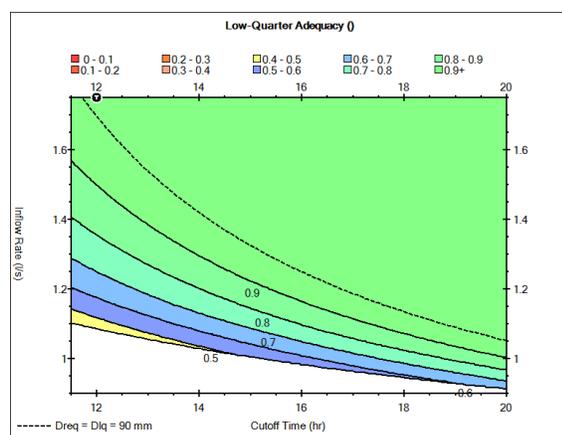


Figure 9.5: Design Analysis 1: adequacy of low-quarter for furrows with q_{in} in the upper 95% percentile

examined directly with the scenario *Inflow rate vs. cutoff time for 600 m × 86 furrow set*.

The results of Fig. 9.4 also show, indirectly, that within a range of q_{in} , $PAElq$ is moderately sensitive to deviations from the design flow if the applied volume is controlled accurately, i.e., if the inflow rate is measured accurately and the cutoff time is adjusted accordingly. This is important to know because, in practice, the flow rate delivered by the farm supply system may differ from the design value. The design q_{in} with an 86 furrow set is 1.76 l/s/furrow. $PAElq$ is 72% or better in the range of 80 to 135 furrows per set, which represents variations in q_{in} of 1.11 to 1.87 l/s/furrow. Evidently, if siphon tubes are used to control the inflow to individual furrows, the set size can be adjusted to keep q_{in} as close to the design value as possible, and therefore the cutoff time. The sensitivity of the proposed scenario is

In furrow irrigation, the mechanism used to divide the total flow causes variation in q_{in} . According to Trout and Mackey (1988), this variability, expressed as a coefficient of variation (CV), can be as much as 15% when using siphon tubes, 25% when using gated pipe, and 29% when using feed ditches. Unit inflow rate variations will cause variations in applied water for the same cutoff time. The design process should quantify the under-irrigation that will result from this variation in applied water. This problem can be examined with the help of an adequacy of the low-quarter ($ADlq$) graph (Fig. 9.5) developed for an individual furrow (see the scenario *600 m X 1 furrow*). With the proposed design, $q_{in} = 1.75$ l/s (27.7 gpm) and $T_{co} = 12$ h, assuming that q_{in} is normally distributed with a CV of 15%, then q_{in}

will be greater than 1.31 l/s for 95% of the furrows. Use the Water Distribution Diagram to select this point, and then inspect that point on the $ADlq$ contour graph. The $ADlq$ for that solution is 0.73. This means that the $ADlq$ of 95% of the furrows will be better than 0.73. The graph also shows that the sensitivity of $ADlq$ to furrow-to furrow inflow rate variations will increase as the design q_{in} decreases. With $q_{in} = 1.75$ l/s and $T_{co} = 12$ h, $ADlq$ will drop below 0.9 only if q_{in} drops more than 15% (below 1.5 l/s/furrow). In contrast, if the design $q_{in} = 1.1$ l/s/furrow ($T_{co} = 20$ h), $ADlq$ will drop below 0.9 with flow rate reductions greater than 10% (less than 1.0 l/s/furrow).

The proposed design assumes known, average infiltration and roughness conditions. In practice, those inputs cannot be determined precisely, and they vary within a field, throughout the irrigation season, and from one year to the next due to soil tillage practices, soil compaction, and surface vegetation and root development (Mailapalli et al., 2008; Meek et al., 1992). This variability can compromise the performance of the irrigation system. Development of statistical measures of irrigation performance as a function of those uncertain inputs is desirable, but that requires knowledge of the statistical distribution of infiltration and roughness conditions. In the best of cases, those conditions will be determined from a limited number of field evaluations. More often, though, the available information will be generic, such as the infiltration family description provided by the USDA-NRCS soils database or the Manning roughness coefficients recommended by NRCS for different soil/crop conditions. The alternative, then, is to use the Simulation World to conduct simple sensitivity analyses with the proposed solution. Only the sensitivity to infiltration will be examined here.

The simulation folder *Sensitivity analysis* tests the proposed solution to variations in infiltration rates, using the 0.45 to 0.8 NRCS infiltration families. This range represents a variation in τ_{req} with the design q_{in} of approximately 6.5 to 13 hr¹. Compare the computed final infiltration profiles with the Data Comparison Tool. Lower infiltration rates decrease total infiltration relative to the irrigation requirement while larger infiltration increases total infiltration. Review the performance measures displayed in the indicator tab (not shown). All losses are by runoff with the 0.45 family while losses are almost entirely by deep percolation with the 0.8 family. As infiltration rates increase, $DUlq$ degrades and the downstream end of the field becomes increasingly under-irrigated. Final advance time decreases by nearly 33% with respect to the design value (5 h) with the smaller infiltration family and more than doubles with the larger one. In contrast, the application efficiency is less sensitive. Application efficiency degrades from 72% to 71% when the infiltration family changes by one value (0.5 and 0.7) and to 70% with the 0.8 infiltration family and to 67% with the 0.45 infiltration family. Likewise, the requirement efficiency is better than 93% in all cases, which indicates that the irrigation requirement is substantially met within this range of infiltration conditions and with the proposed set size, inflow rate, and cutoff time, despite the large variation in final advance times and runoff rates. If seasonal infiltration rate variations can be anticipated, it may be possible to adjust the furrow set size, and therefore the unit inflow rate, to maintain performance at peak levels.

¹ τ_{req} is displayed in the Soil/Crop Properties tab for each scenario.

The aforementioned results were developed based on the NRCS infiltration families, which vary the average infiltration with the average inflow rate. As noted in Section 5.4.2, with free-draining systems, distribution uniformity decreases when accounting for the local variation in wetted perimeter in comparison with simulations that ignore that effect. The sensitivity of the predicted performance to the infiltration modeling approach is explored with the scenarios in the folder *Sensitivity of infiltration with the WGA equation*. These simulations account for wetted perimeter effects using the **Local Wetted Perimeter** option in combination with the Warrick-Green-Ampt infiltration equation. The WGA parameters for each case were calibrated to produce similar long-term infiltration rates as those predicted with the infiltration families. Hence, the $K_s = 0.3, 0.35, 0.4, 0.5$ and 0.6 mm/hr scenarios approximate, respectively the 0.45, 0.5, 0.6, 0.7 and 0.8 infiltration family scenarios. Execute both sets of scenarios and examine them with the Data Comparison Tool (not shown). For each pair of scenarios, for example the $K_s = 3$ mm/hr and $IF = 0.45$ scenarios, advance and recession times are reasonably similar while the final runoff rates are in close agreement. As expected, computations with the WGA equation result in a lower distribution uniformity, but the effect is minor and translate into an even smaller effect on application and requirement efficiency. Hence, while the infiltration modeling approach is a source of uncertainty in the design of furrow irrigation systems, in this example it is a minor issue in comparison with the variability of infiltration.

9.4.2 Borders and basins

This case folder contains three design scenarios, one for a sloping border, the second for a level-basin, and the last for a near-level border. The field dimensions, available inflow rate, and infiltration conditions (0.6 NRCS Infiltration Family) are the same as for the sloping furrow example. In all cases, the scenario analyzes performance as a function of **Length vs. Inflow Rate for a Given Border Width** (Option 2). The analyses consider a unit border width (1 m = 3.3 ft). Often, designs are easier to interpret when based on the flow per unit width (or per furrow).

9.4.2.1 Sloping border

This example uses the same bottom slope same as the sloping furrow scenario but the Manning roughness coefficient is larger, 0.15. This value is typical of borders with vegetation. The contouring range was set to 100 m to 600 m for the length and from 0.5 to 5 l/s for the width. This corresponds to border widths between 300 m and 30 m, respectively, if $Q_{in} = 150$ l/s. With this contouring range, the application-selected tuning point coordinates are 600 m \times 2.8 l/s. Complete the tuning computations and note that the default tuning point is a point of relatively low PAEmin. Select instead 600 m \times 5 l/s as the new tuning point.

The resulting contours (Fig. 9.6) show that the unit inflow rate (l/s/m) must increase as field length increases to achieve acceptable levels of performance. Thus, longer fields will

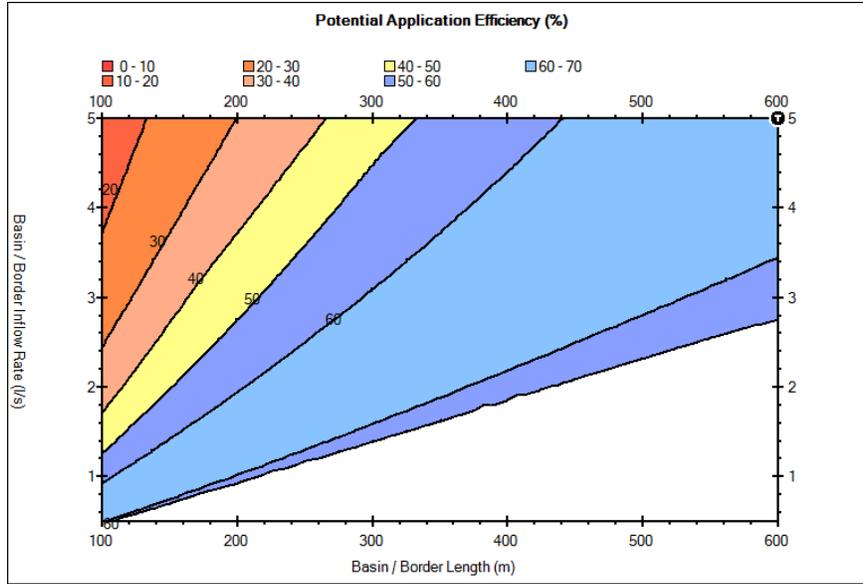


Figure 9.6: Graded border design: PAEmin contour

require a narrower border for a given total inflow rate. If the longer length is selected, a q_{in} of 5 l/s/m is needed to achieve peak performance, which translates into a 30 m wide border. The graph suggests that acceptable performance can be achieved with even longer lengths, but as was noted in the previous chapter, the potential for erosion and over-topping are factors that limit the maximum q_{in} that can be applied to the field. There are additional factors that need to be considered when recommending a set length. With long fields, it becomes increasingly unlikely that field conditions will be uniform as assumed in the design. Hence, one can expected the predicted performance to be increasingly sensitive to conditions different from those assumed in the design with greater lengths. Shorter fields should reduce the sensitivity and provide flexibility to deal with unforeseen circumstances, but this has to weighted against use of farm equipment, set duration and their effect on labor management, the land surface lost to border ridges, and the construction cost for supply channels and permanent outlet structures. These considerations apply to all system types.

9.4.2.2 Level basin

The level basin design scenario differs from the previous example in that the slope is zero and the downstream end is blocked. Finding an acceptable tuning point can be difficult with level basins because the region of high performance is relatively small. In addition, level systems generally require the inflow to be cutoff before the stream reaches the end of the field while tuning calculations assume that cutoff occurs post-advance. Using the same contouring range as with the graded border example, run the tuning calculations with the default tuning point (600 m \times 2.8 l/s). This calculation produces a warning because the resulting PAE_{min} is low while the inflow needs to be terminated before advance is complete (i.e., the cutoff ratio XR is less than 1.0). This will produce inaccurate contours in the region of best performance. The warning includes a message offering the user to either test a software-

selected tuning point (*Yes, retry at the suggested point*), or to calculate the contours with the results of the current tuning point (*Press No to keep the current point*). Since the logic used by the program to find an alternate point is rudimentary, the recommended approach is to keep the current results and use them to generate approximate contours. Those results can then be used to find a tuning point manually that will increase PAE_{min} above 60% and XR above unity. To this end, before computing the contours, press the **Add Contour** button to create a combined PAE_{min} and XR contour graph, also referred to as an overlay.

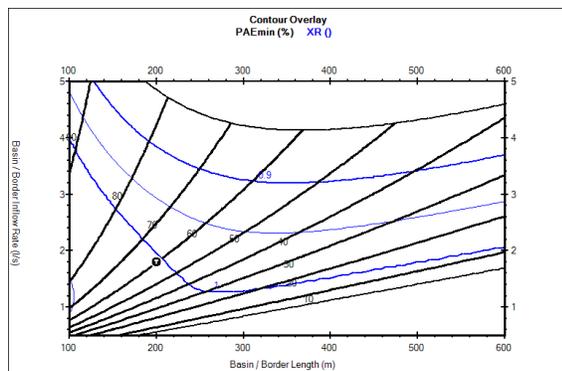


Figure 9.7: Level basin design: Overlay of PAE_{min} and XR contour graphs

Figure 9.7 shows the resulting combined PAE_{min}/XR contour graph. The tuning point is located on the right hand side of the graph and is clearly inadequate. Although inaccurate, these contours suggest that the point $200\text{ m} \times 2.4\text{ l/s}$ could be closer to meeting the tuning requirements. Run the tuning calculations with this point. This will again produce a warning because the selected point still does not meet the constraints. Use again these temporary results to compute a new set of contours. From these contours, a better location for the tuning point is $200\text{ m} \times 1.8\text{ l/s}$. The application will report that tuning calculations were successful. Use these results to generate the final design contours.

Unlike the graded borders of the previous example, the contours (Fig. 9.7) show that high values of PAE_{min} cannot be attained beyond some length, even with very high inflow rates. An important feature of the design contours for level basins is the limit line associated with $XR = 0.85$. This line was suggested by Clemmens and Dedrick (1982) as a reasonable limit for the minimum value of XR that can be tolerated in the design. For a given length, infiltration, roughness, and irrigation requirement, performance is sensitive to q_{in} within a limited range. Above a certain q_{in} , performance is a function of the applied volume and requires proportionately smaller values of XR to maintain the design DU_{min} . When navigating the contours with the cursor above the limit line, the application displays a message indicating that the line has been exceeded. While level systems require large unit inflow rates, using extremely large inflows is not recommended for other reasons besides erosion. One is that with a small XR , the potential for incomplete advance increases if infiltration and/or roughness conditions differ from those assumed in the design. Another factor is that as set times become shorter, labor management becomes more difficult and performance becomes more sensitive to small errors in the cutoff time. The design limit is not exact (Clemmens and Dedrick, 1982), but it is a practical compromise between performance, robustness, and ease of operation. Exceeding the limit line is justified if supported by comprehensive sensitivity analyses.

For the example, a possible design recommendation is to cut the 600 m long field in half, but PAE_{min} is only 74% when $XR = 0.85$ ($q_{in} = 3.6\text{ l/s/m}$), and improves only slightly with larger q_{in} values. PAE_{min} can be improved by reducing the basin length to 200 m.

With this length and $XR = 0.85$, the predicted PAE_{min} is 87% ($q_{in} = 4.3$ l/s/m), but this selection requires unequal set sizes. A practical choice is $q_{in} = 4$ l/s/m, which requires dividing the field into 48 sets (200 m long \times 37.5 m wide, 0.75 has = 1.85 ac). The projected PAE_{min} is 85% while the set time is 1.5 h, which is easy to manage. Note that the set size is limited by the available total inflow rate and that a larger inflow would allow increasing the set width, but not the length.

The reader is encouraged to run sensitivity tests with this solution, with the cutoff time as given, but also using XR as the cutoff criterion. In this regard, it should be noted that the design procedures, which are based on volume balance and are therefore approximate, result in an XR value of 0.87. Unsteady simulation results with $q_{in} = 4$ l/s/m and $T_{co} = 1.5$ h yield $XR = 0.84$. The slight differences between solutions can be observed in the Hydraulic Summary tab. Hence, conduct the sensitivity tests with $XR = 0.84$ as the cutoff criterion. When infiltration rates are greater than in the design, it is safer to determine cutoff based on distance, even though there is a slight penalty in performance.

9.4.2.3 Near-level basin

The only difference with respect to the previous example is that the bottom slope is 0.02%. Contours were developed again in the range 100 – 600 m for the length and 0.5 to 5 l/s/m for q_{in} . In this case, the application reports a successful calculation of the tuning factors with the default tuning point. However, examination of the resulting contours reveals that this is a point of poor performance and that an alternate tuning point is required. Compare also the volume balance and unsteady flow solutions shown in the Hydraulic Summary tab and notice that differences are noticeable. As with the level basin case, use an overlay of the PAE_{min} and XR contours to find a better location for the tuning point. From the graph, the point 200 m \times 1.4 l/s/m appears to be a reasonable location. Running the tuning calculations with this point and, subsequently, the contour calculations confirms that this is an adequate selection.

Except for the XR contours, the contours for the near-level system are very similar to those computed for the level system. Figure 9.8 shows the PAE_{min}/XR overlay for this example. In particular, results show that PAE_{min} is primarily limited by length. One key difference is that with near level systems, for a given length, PAE_{min} initially improves with increasing q_{in} , becomes relatively insensitive at high enough values, and then decreases, albeit slightly. The reason for this decline is that with near-level systems, the point of minimum infiltration shifts from the downstream end of the field to, ultimately, the upstream end with sufficiently large q_{in} . Performance then is limited by the opportunity time needed at the upstream end of the field. The shift in the point of minimum infiltration also explains why the same XR value can apply to two different q_{in} values at a given length, as can be seen by comparing the XR contours for the level and near-level scenarios. Another important difference to note between the two sets of contours is that the curves for the near-level system are relatively jagged. This is because volume balance calculations are the least accurate for near-level systems in comparison with graded, open-end or level basin systems. It

is particularly important with these systems to compare the volume balance and unsteady simulation results for a selected solution point using the **Hydraulic Summary** tab.

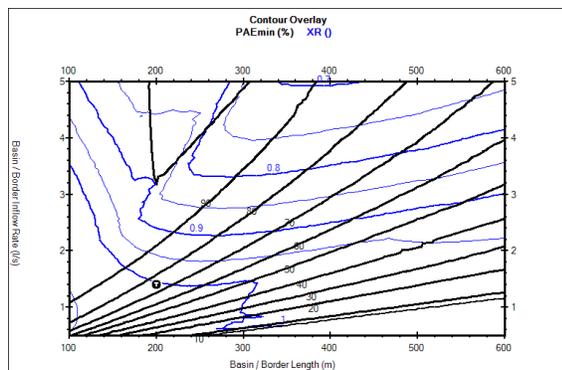


Figure 9.8: Near-level basin design: Overlay of PAE_{min} and XR contours

1/s/m ($XR = 0.94$) and improves to 96% with $q_{in} = 3$ l/s/m ($XR = 0.86$). The corresponding set widths are 75 and 50 m, respectively, while the areas are 1 and 1.5 has (2.4 and 3.7 ac). As with other system types, sensitivity analyses need to be conducted to evaluate the robustness of these alternative designs.

The results of Fig. 9.8 suggest that a 200 m long basin is needed to achieve peak performance, as with the level basin case. No theoretical design limits have been developed for near-level basin systems similar to those available for level basins. Nevertheless, considering the similarities between the level and near-level systems, it makes sense to avoid extremely large inflow rates and seek solutions for which $XR \geq 0.85$. Note that PAE_{min} can be improved with respect to the level basin case with a smaller q_{in} . Evidently, this means that the set width can be increased. Use the Water Distribution Diagram to study the variation in PAE_{min} with q_{in} for a length of 200 m. PAE_{min} is 88% when $q_{in} = 2$

Part III
Advanced Features

ADVANCED SIMULATION OPTIONS

10.1 Solute Transport

See Section 2.1.1 for an overview of the solute transport model.

10.1.1 Inputs

Common inputs Setting the User Level to Advanced will display the Fertigation checkbox in the Simulation Start tab page. Use the checkbox to enable fertigation simulations. This will display an additional input tab page, Fertigation. Enter all pertinent simulation data (geometry, infiltration and roughness, boundary conditions) as with conventional simulations.

Fertigation tab This tab page is used to specify the solute mass injection rate and computational options of the advection-dispersion solution.

Solute mass injection rate: The solute mass injection rate depends on the known solute concentration (mass per unit volume M/L^3) in a supply tank, and the known solution injection rate (volume per unit time L^3/T). The solution concentration is specified with Tank Concentration input box, while the Injection Table specifies the solution injection rate. The injection rate data are plotted next to the table, as shown in Fig. 10.1. The example shown in the figure is included in the *Simulation Examples.srfr* file, Fertigation folder. In the example, the solute is injected in six 10 min pulses, each pulse 15 min apart. The model assumes that the injection rate varies linearly between consecutive tabulated values. Step changes in the injection rate are represented using small time intervals, half-a-minute in the table, to avoid computational difficulties caused by rapid changes

Advanced Simulation Options

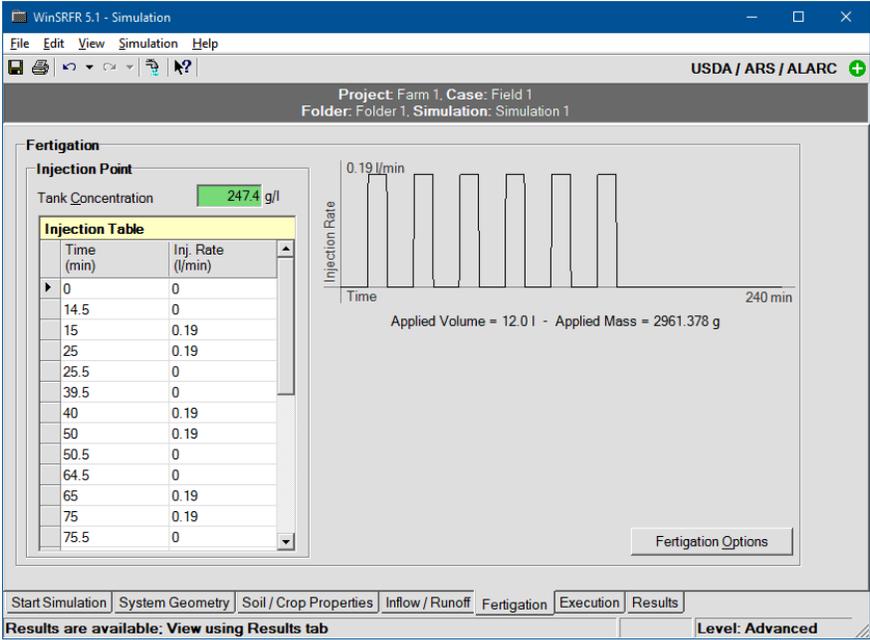


Figure 10.1: Fertigation tab page.

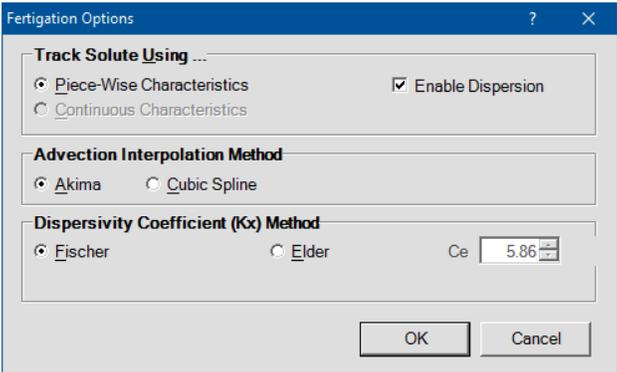


Figure 10.2: Fertigation options.

in boundary conditions. For practical studies, in which the solute is injected as a single, long-duration pulse, use of very small intervals to represent a step change in discharge is unwarranted.

Fertigation Options: This form (Fig. 10.2) is displayed by pressing the Fertigation Options button. In all transport process described by advection and dispersion, advection is the primary mechanism. The checkbox labeled Include Dispersion is used to determine if the model will calculate advective transport only (unchecked), or both advection and dispersion (checked). Considering typical fertigation scenarios, involving a single long-duration solute pulse, and where the solute mixes completely with the water at the injection point, dispersion is minor relative to advective transport.

Dispersion calculations require specifying a longitudinal dispersion coefficient K_x [L^2/T]. Few studies have calibrated this coefficient under irrigation conditions. García-Navarro et al. (2000) determined a value of $K_x = 0.075 \text{ m}^2/\text{s}$ from their border irrigation experiment. Since the experiment was conducted on a narrow border with no infiltration, it is unclear if this value is more widely applicable. Although various methods for the estimation of K_x have been proposed from solute transport studies in natural streams, those methods can produce estimates that are orders of magnitude greater than reported K_x values for surface irrigation. Currently, the program calculates the dispersion coefficient with an equation proposed by Elder (1959), or uses a specified dispersivity value. The former method adjusts K_x in space and time depending on nodal flow conditions (flow velocity and depth) while the latter uses the same constant value, independently of those conditions. The Elder equation was implemented in WinSRFR with a user-adjustable coefficient C_e .

10.1.2 Outputs

A fertigation simulation adds three output forms to those produced with conventional simulations, shown in the following table:

The Simulation Network (F7) provides additional outputs. Running a solute transport simulation will enable two buttons at the top of the irrigation viewer, **Highlight Solute** and **Show Characteristics**. The first button displays the path of the transported solute with time. After enabling, the label in the button will change to **Clear Solute**, as shown in Fig. 10.3. The second button displays the grid used to compute advection (continuous characteristics if using advection only, or segments of characteristics, if using the full advection-dispersion model). When enabled, the label will change to **Hide Characteristics**.

Table 10.1: Fertigation outputs.

Tab page	Description
Fertigation	Numerical summary of the final solute mass balance and fertigation performance indicators.
Profiles(Fertigation)	Graphical display of applied fertilizer as a function of distance at selected times. The times are the same as those used for display flow depth and water surface elevation profiles.
Hydrographs (Fertigation)	Graphical display of applied fertilizer as a function of time at selected distances. The distances are the same as those used for display flow depth and flow rate hydrographs.

10.1.3 Example

A fertigation simulation example is provided in the *Fertigation Examples.srfr* file. This example was reported by Strelkoff et al. (2006). The tank concentration and injection rate are as depicted in Fig. 10.1. The folder contains two scenarios, Pure Advection and Advection-Dispersion. Execute these two scenarios and examine the outputs. Figure 10.4 compares the outputs displayed in the **Profiles (Fertigation)** tab. The solute infiltration profiles are very similar but, as expected, the solution computed with dispersion shows slight attenuation of the peaks in relation to the solution computed with pure advection.

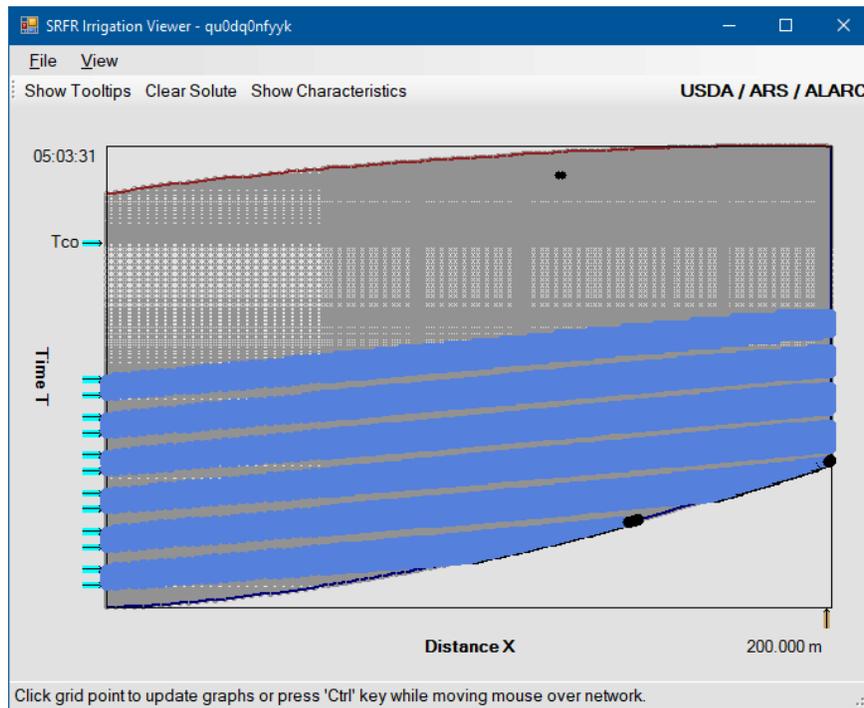


Figure 10.3: Irrigation viewer displaying the path of the transported solute.

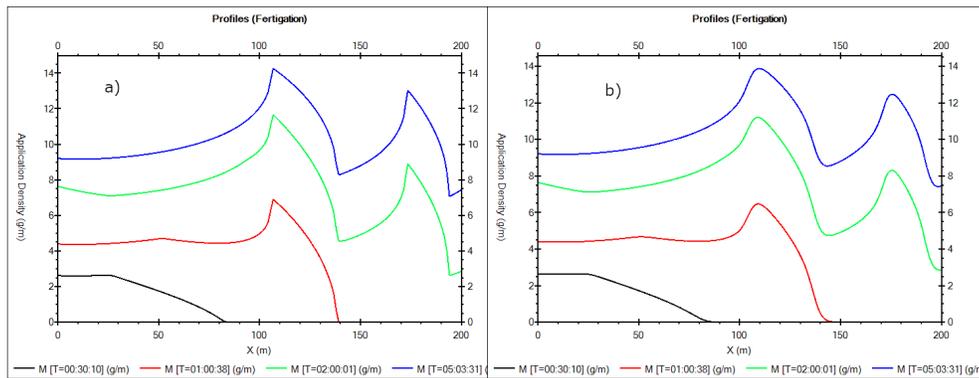


Figure 10.4: Solute profiles computed with the fertigation module: a) solution computed with pure advection, and; b) solution computed with advection-dispersion.

10.2 Simulation with Infiltration Given by the One-Dimensional Richards Equation

This option, available only for border/basin irrigation, couples the simulation engines of WinSRFR and of the HYDRUS-1D (Šimůnek et al., 2013) software package (SRFR.dll and Hydrus.dll, respectively). This modeling approach was developed mostly for research purposes. It is computationally intensive and time-consuming and has limited ability to recover from computational incidents. Users must be reasonably familiar with HYDRUS-1D. A basic understanding of the coupling method, known as external iterative coupling (Bautista et al., 2010), is needed to properly set up a simulation.

In external coupling, the irrigation and infiltration equations are solved separately, sequentially, and iteratively. Calculations begin by solving the Richards equation with HYDRUS-1D, using an assumed upper boundary condition. This boundary condition, the water pressure applied at the soil surface, is an initial estimate of the flow depth calculated by the surface flow equations. Since flow depths vary along the field, HYDRUS-1D calculations need to be carried out, in theory, at every discrete spatial location used for the surface flow calculations (i.e., at every x-grid point generated by SRFR simulation engine). Instead, a selected number of x-grid points is used for these calculations. These selected x-grid points are designated as coupling distances.

The infiltrated depth vs. time series calculated with HYDRUS-1D represent the infiltration functions needed to solve the irrigation flow equations with SRFR. In the SRFR calculations, infiltration values at intermediate x-grid points are interpolated from the infiltration time-series computed at the coupling distances. The irrigation simulation produces flow depth hydrographs (flow depth as a function time) at all x-grid points in the SRFR computational grid. The flow depths computed at the coupling distances represent the new estimate of the upper boundary condition needed to simulate infiltration with HYDRUS-1D. HYDRUS-1D calculations are then repeated for each coupling distance. These results are supplied to the next SRFR simulation, which then once again generates flow depth hydrographs at the coupling locations. Convergence is achieved when changes in the infiltrated profile computed by SRFR become negligible.

The first step in setting up a simulation is specifying all pertinent geometry, roughness, and boundary condition options, as with any other WinSRFR simulation scenario. In the Soil/Crop Properties tab, click on the Infiltration Function control, and from the list select Richards (HYDRUS-1D). The setup involves three additional steps, namely:

1. Setup the HYDRUS-1D project files. If infiltration is spatially uniform then only one HYDRUS project is needed, but two or more are needed if infiltration is variable.
2. Each of these projects must associated with a distance along the field. If infiltration is spatially uniform, then a single project is needed. That project is implicitly assigned to the upstream end of the field ($x = 0$). If infiltration is spatially variable, then a project

must be assigned at every location where infiltration changes. This step also specifies the subdirectory path to the HYDRUS-1D project files to be used for a simulation.

3. Specify the coupling distances.

These steps will be explained below.

10.2.1 HYDRUS-1D Installation

This computational option was implemented in combination with HYDRUS-1D V4.16.0080. The software is available for download free of charge from the PC-Progress website¹. Since HYDRUS-1D uses text files for input and output, the routines used to extract data from HYDRUS-1D and write SRFR outputs back to HYDRUS are not guaranteed to work with earlier versions of that software.

The WinSRFR software package includes the dynamic link library HYDRUSAPI.dll. This dll verifies that HYDRUS-1D has been installed and determines the path to HYDRUS.dll, checks the setup specified by the HYDRUS-1D project files, manages data exchanges with SRFR, and monitors two output files, Balance.out and Error.msg, which report simulation errors.

HYDRUSAPI.dll interacts with three HYDRUS-1D project files, *Selector.in*, *Atmosph.in*, and *T_Level.out*. With each iteration, HYDRUSAPI.dll modifies the simulation start and stop times, and the number of Time-Variable Boundary Condition records in the *Selector.in* file. It also extracts from this file the units of the time and flow and infiltrated depth data. The initial estimate of the flow depth at each coupling distance, and the flow depth hydrographs computed by SRFR during each iteration of the external iteration loop is written to the *Atmosph.in* file. Finally, the infiltration time series computed by HYDRUS-1D is extracted from the *T_Level.out* file.

HYDRUSAPI.dll checks several setup options in the HYDRUS-1D project files. If the check fails, the execution is terminated and a diagnostic message is issued. HYDRUSAPI.dll cannot change the setup in the HYDRUS-1D files - those changes must be made by the user through the HYDRUS-1D GUI (the recommended approach) or by editing the *Selector.in* and *Atmosph.in* files.

10.2.2 Setting Up the HYDRUS Project Files

The Richards equation option can be used to model water flow only or to model water flow in combination with solute transport. Instructions for setting up a HYDRUS-1D simulation for these types of simulations are provided in the HYDRUS-1D manual (Šimůnek et al., 2013). Except for the options described below, the setup is independent of WinSRFR.

¹<http://www.pc-progress.com/en/Default.aspx?H1d-downloads>

Advanced Simulation Options

The user can select any number of soil materials, soil hydraulic model, water flow parameters, initial condition option, and lower boundary condition options offered by HYDRUS-1D.

Figure 10.5 displays the HYDRUS-1D GUI. The icons on the left represent groups of input (Pre-processing) variables. If the simulation is successful, the available groups of outputs (Post-processing) will be listed on the right. The Main Process, Time Information, Print Information, Water Flow-Boundary Conditions, and Variable Boundary Conditions groups contain variables that require specific settings. Pressing on any of those icons will display an input screen.

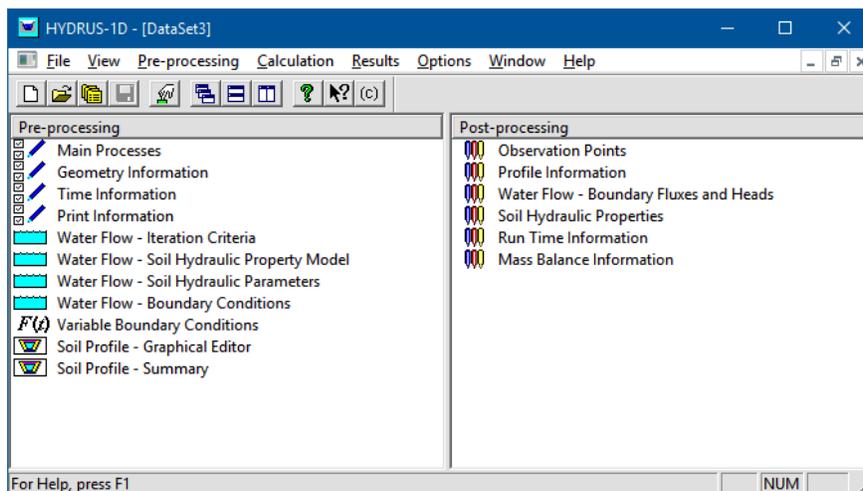


Figure 10.5: HYDRUS-1D main screen, displaying input variables groups on the left and output groups on the right.

Main Processes: Enable Water Flow only if simulating water flow only or Water Flow and Solute Transport/Standard Solute Transport if modeling a fertigation event.

Time Information: The HYDRUSAPI. Dll assumes that outputs will be captured at 1 min intervals. Hence,

- Set Time Units to Minutes.
- Set the Initial Time Step to 1 min or less.
- Enable Time-Variable Boundary Conditions.
- Set the number of time variable conditions to 1.

During a simulation, HYDRUSAPI. Dll will overwrite the Initial and Final Times. Therefore, default values or arbitrary values can be assigned to those variables.

Print Information: Under Print Options, disable all options except Enable Print at Regular Time Intervals.

- Set the Time Interval to 1 min.
- Set Number of Print times to 1.

Water Flow-Boundary Conditions: Set the Upper Boundary Condition to Variable Pressure Head. Currently the application assumes that the field will not dewater during an irrigation event. The Lower Boundary Condition and Initial Condition can be set with any of the available options

Variable Boundary Conditions. If the Number of Time-Variable Records was given as 1 in the Time Information screen, a single record will have to be entered here. This record consists of a time value and a water pressure (htop in the HYDRUS nomenclature). Although both values will be overwritten by the HYDRUSAPI.dll, the time value must set equal to the Final Time specified in the Time Information screen. Otherwise HYDRUS-1D will issue an error message and prevent the user from editing other data until the error is corrected.

The HYDRUS-1D project file(s) need to be tested independently prior to attempting a simulation in combination with WinSRFR. Those tests need to be conducted for a reasonable simulation time and upper boundary conditions considering the irrigation problem to be analyzed. For example, the Final Time can be set to the expected cutoff time (or a larger value), and the time-variable boundary condition to a reasonable value. Typical irrigations flow depths are between 5 and 10 cm (2 to 4 in).

Successful independent execution of a HYDRUS project does not guarantee successful execution in combination with the SRFR.dll. At least two problems can arise. One is that the HYDRUS simulation may fail in combination with upper boundary conditions generated by SRFR. Unsuccessful HYDRUS simulations will be reported by WinSRFR.

Another problem is caused by temporary dewatering of part of the previously wetted field (front-end recession and re-advance), which can be induced by inflow rate variations. This causes an incorrect calculation of infiltration. The simulation may appear to be successful, but the results will be erroneous. The user needs to check the advance-recession output for indications of front-end recession. Also, when using the HYDRUS-1D option, the Results/Infiltration tab will display the computed infiltration profile and the infiltration computed at the calibration points. Results are in error if the calibration point infiltration does not match the infiltrated profile generated by SRFR.

HYDRUS-1D project files can get corrupted after an unsuccessful simulation. When attempting to reuse those files, WinSRFR will issue an error message. Several options are available for dealing with this problem. A new project file can be created. If you are familiar with the structure of the HYDRUS-1D text files, you can edit those files manually. A simple solution is to always keep a backup copy of a working HYDRUS-1D project. Finally, you can keep HYDRUS-1D and the working project in memory and use the Save As command to resave the project if an incident occurs. This will save the files with data stored in memory.

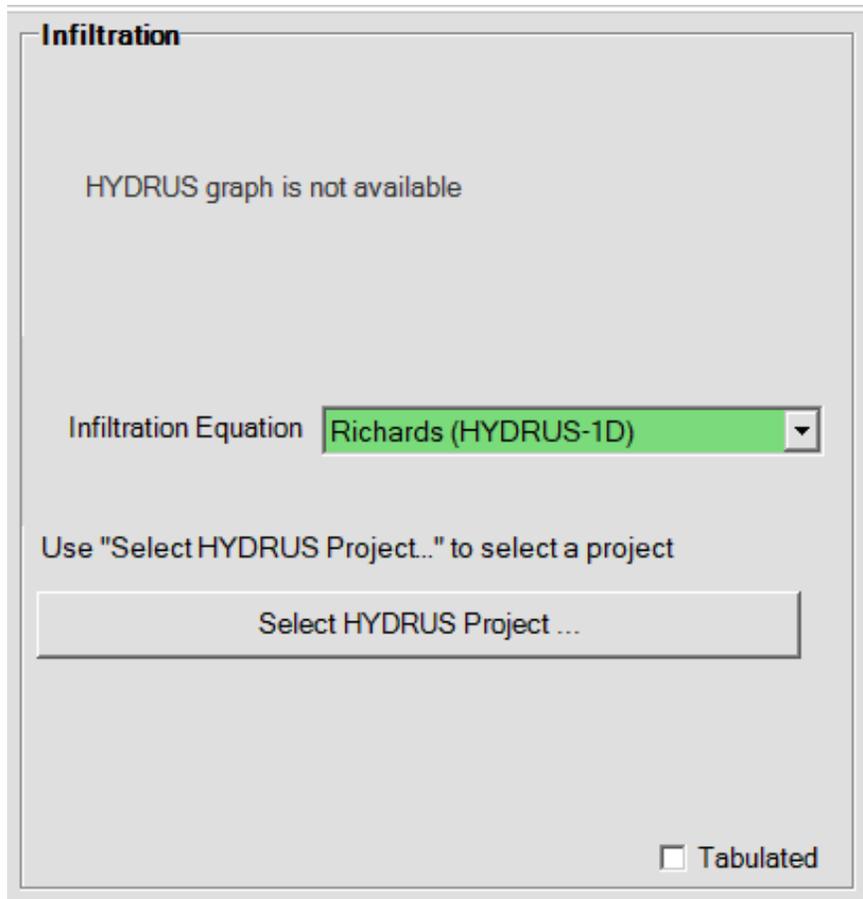


Figure 10.6: Simulation with the Richards Equation: Selecting the HYDRUS project files.

10.2.3 Selection of the HYDRUS Project Files and Coupling Distances

After selecting the Richards infiltration equation option, the program will display the Select HYDRUS Project button (Fig.10.6). If infiltration is spatially uniform, then a single HYDRUS-1D project needs to be provided and that project is automatically applied to the head-end of the field. Press this button to select the folder containing the HYDRUS-1D project files. This folder is created automatically by HYDRUS-1D using the same name as the project file. For example, if working with a HYDRUS-1D project called Example1.h1d, located in directory H:\, files for that project are stored in a subdirectory *H:\Example1*. The WinSRFR project file does not need to be stored in *H:* and can be named differently.

As with other infiltration equation options, use the Tabulated checkbox to specify spatially variable infiltration. Assign different HYDRUS-1D project files at locations where infiltration conditions change using the displayed input table. The table can be populated using cut-and-paste or using its context menu, which is displayed by right-clicking on the left margin of the table.

The last step prior to execution is to specify the number and location of the coupling distances with the **HYDRUS Coupling Distances** table. Results can be expected to change but eventually stabilize with an increasing number of points. However, increasing the number of coupling distances will also increase the computational time. Coupling distances can be specified automatically (at WinSRFR distances, default option) or manually (at User Distances). In the former case, the number and location of coupling distances depends on whether infiltration and/or bottom slope are spatially uniform or variable. In the simplest of cases, uniform infiltration and bottom slope, the software selects 5 (nearly) equally spaced locations. Current experience with the automatic selection of coupling distances suggests that the rules used work well under various soil and hydraulic conditions. Still, a good practice is to run an initial simulation with the automatic selection, then run a second simulation with a larger number of coupling distances, and compare the results. Continue to increase the number of calibration points until changes become negligible.

With free-draining systems, flow depth varies substantially near the boundary due to the applied boundary condition (critical flow). Although the effect of the boundary condition extends over a short distance, the simulated infiltration profile could be substantially different near the end of the field if the last coupling distance is near the downstream boundary or at the boundary. With the WinSRFR Distances option, the application selects a location near the boundary. The influence of this uncertain point will diminish as the number coupling distances increases.

10.2.4 Setting up WinSRFR and HYDRUS-1D Files for Simulations Involving Water Flow and Solute Transport

Options used to run fertigation simulations were discussed in Section 10.1. As with the water flow data, the surface solute hydrographs calculated by SRFR will be extracted by the HYDRUSAPI.dll and written to the *ATMOSP.H.in* file. Thus, for each calibration point, HYDRUSAPI.dll modifies the simulation start and stop time, the number of Time-Variable Boundary records, the Time Variable Boundary Condition table (specifically, the Time, hTop and cTop columns). Water flow outputs generated by HYDRUS (infiltration) will be extracted from the *T_Level.out* file while subsurface solute flow outputs will be extracted from the *Solute1.out* file.

The following options must be set through the HYDRUS-1D GUI.

Main Processes screen: In addition to Water Flow, enable the Solute Transport + Standard Solute Transport options. All other options need to be disabled.

Solute Transport-General Information: This setup assumes that the simulation involves a single, conservative solute.

- Enable Equilibrium Model
- Set Number of Solutes to 1 (Pulse Duration will be set by the HYDRUSAPI.dll)

Solute Transport Boundary Conditions: The Initial Condition for the solute should be to zero (set with the Soil Profile Graphical Editor). If solute (fertilizer) is already present in the soil profile and its concentration is known, then it would be appropriate to set the initial condition to a non-zero value.

- Set Upper Boundary Condition to Concentration Flux BC
- Set Initial Conditions to Liquid Phase Concentration (mass solute/volume water)

10.2.5 Examples

Examples are provided in the file *HYDRUS Coupling Examples,srfr*. The example was used by Bautista et al. (2010) to test the external coupling procedure and is identified in that reference as Data Set 3. The low-gradient border is 150 m long and is irrigated with a unit inflow rate of 3 l/s/m. The simulation uses the default soil hydraulic parameters for a sandy clay loam suggested by the HYDRUS-1D program. The HYDRUS-1D project files are located in the Examples/Hydrus subdirectory. Use the *DataSet3.h1d* file to view the project in HYDRUS-1D. To run the example, you need to set the path to the subdirectory */DataSet3*. Before running these examples, copy the HYDRUS project files to a directory of your choice, different from the installation directory. Reset then the path for the HYDRUS-1D project files, from the Soil/Crops Properties tab. You will then be able to preserve an original copy of those files, if you need to restore them.

- Scenario 1. This scenario uses the default coupling distances (WinSRFR distances).
- Scenario 2. This scenario uses customized coupling, with the last coupling distance at the downstream boundary. Compare these results with those of Scenario 1 to see the effect on the infiltration profile near the boundary. This reflects the influence of the small depth computed at the boundary, where a critical flow condition applies. With free-draining systems, the recommendation is to place the last coupling distance slightly upstream from the downstream boundary.
- Scenario 3. This scenario uses 3 times as many coupling distances as Scenario 2, with the last distance near the downstream boundary. Execute this scenario and compare the summary results and simulation time.

If infiltration is spatially variable, different HYDRUS-1D projects needs to be assigned to distances where infiltration changes, using the **Tabulated** control. You may want to test this option by making copies of the DataSet3 project and changing, for example, the hydraulic conductivity.

CHAPTER 11

WORKING WITH SCRIPTS

WinSRFR 4.1 introduced batch simulation functionalities. Two approaches are available. One is to develop an external application that calls the simulation engine, SRFR 5. SRFR 5 has an Application Programming Interface (API) that exposes many of its objects to users. Programming expertise is required to use this approach. The second approach, discussed in this section, is to use scripts, a rudimentary programming language internal to the application. The scripting language of WinSRFR is a mechanism for communicating with the user interface. It was developed for research purposes prior to the development of SRFR 5 and its programmable API. Scripts are easy to use and no programming experience is required. However, since scripts interact with the user interface, a batch job implemented with scripts will necessarily run more slowly than one implemented directly with the SRFR 5 API. Selecting the best approach for a particular batch job will depend on the job data input/output requirements and whether those requirements can be met with scripts, the number of simulations that need to be executed, and the time needed to develop an application that calls the SRFR 5 API. With a little bit of experience, batch job can be generated in just a few minutes with scripts.

There are two types of scripts. Command Line Scripts are used to set computational options, such as selecting between furrow/ basin/border, set singled-valued inputs such as field length or a flow rate value for a standard hydrograph, and running a simulation. They cannot be used to input series data, such as a tabulated inflow hydrograph (discharge vs. time). Command Queries retrieve outputs and save them to a file. Singled-valued and series outputs can be extracted with Command Queries.

Scripts are provided to WinSRFR as text tables. These tables, called Tabulated Scripts, can be written as either tab or comma-delimited files (with a .txt or .csv extension, respec-

tively). Any spreadsheet program can be used to create a tabulated script .csv file while any text editor can be used to create and edit .txt files. Separate tabulated scripts are needed for input and output.

11.1 Run Multiple Simulations Dialog

A batch job is executed from the Simulation World by selecting the *Simulation/Run Multiple Simulations* menu command. This will bring up the **Run Multiple Simulations** dialog (Fig. 11.1). Required inputs are:

Input File: Enter the name of the tabulated script input file in this field. This is a read-only file. It is used to specify the inputs for each simulation in a batch job. Optionally, it also specifies the names of files to which time-series outputs (e.g., Advance, Recession and Infiltration) will be saved.

Output File: Enter the name of the tabulated script output file in this field. This is a read/write file that will be modified during execution of the batch job. The file specifies the single-valued outputs that that will be saved after each simulation. Outputs from each run are appended to the end of this file.

Pre-Clear Results: This check box determines what will happen with previously computed results in the output file. If this box is cleared, old outputs will be preserved and new outputs will be appended to the end of file. If the box is checked, old results will be removed before storing new results.

Show Message on First Error: This check box determines how the application will handle warning messages from the SRFR engine. The SRFR engine will issue those messages when the simulated event lasts longer than a week or when the allowable number of computational time steps is exceeded. If the box is checked, the application will allow the SRFR engine to generate a warning. Then, execution of the batch job cannot continue until the user responds to the message. If the box is cleared, the messaging system will be disabled. The application will terminate the particular simulation, write an error report to the output file, and continue the batch job without further user input.

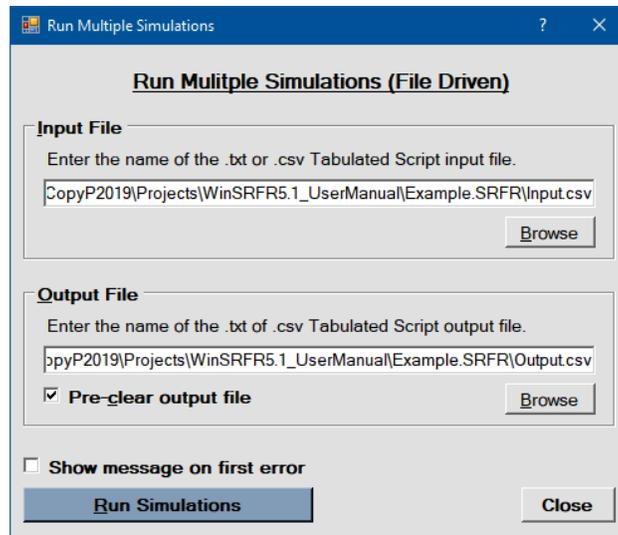


Figure 11.1: Dialog form for batch simulations

11.2 The Scripting Language and the Script Recorder

A script is a text string that is used to build and parse a command. The syntax is defined by the Command and Query script languages. These languages can be displayed with the Script Recorder, which is accessible from the Simulation World’s File menu (*Scripting/View Command Language* or *Scripting/View Query Language*).

Figure 11.2 is a screenshot of the Script Editor displaying part of Command Script language. The lines preceded by an apostrophe are comments. Other lines are elements of the script language. The first word in each line is a keyword that represents a variable name. Keywords are closely related to the variable names displayed by the user interface and, thus, are self-explanatory. As will be described in the following sections, keywords are used as column headers in a tabulated script. The remainder of each line identifies either the data type or the possible value(s) for that variable. For example,

- CrossSection Basin | Border | Furrow: CrossSection is the keyword (column header) while Basin, Border or Furrow are the values that can be assigned to that variable as data in the tabulated script file. Hence, the Command Script “CrossSection Basin” sets the system type to Basin.
- Slope double: Slope is the keyword and, thus, a column header. The data for this variable is a double-precision value. The script “Slope 0.004” sets the field slope to the value 0.004.

An example of the Query Language is displayed in Fig. 11.3. The Query language depends on the outputs generated by a simulation and, thus, is viewable only after running a simulation. As in the Command Language, the first word in each line is the keyword. The rest of the line describes the type of data returned by the query, for example:

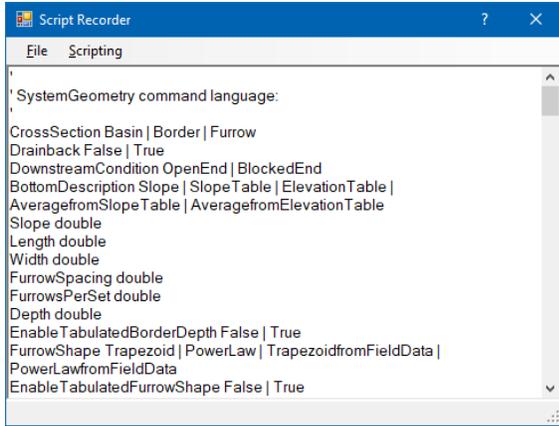


Figure 11.2: Script Editor displaying a part of the Command Script Language

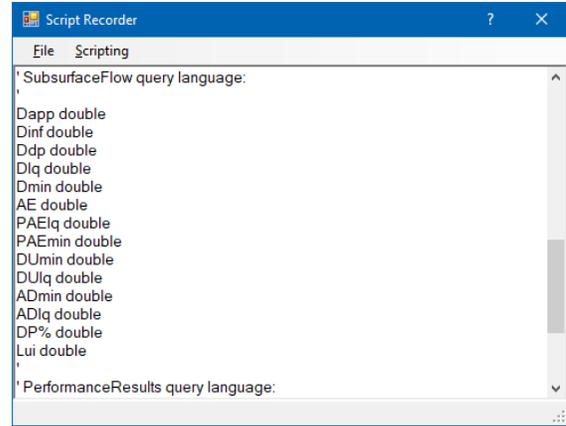


Figure 11.3: Script Editor displaying part of the Query Script Language.

- Dapp double: Dapp is a keyword and double indicates that a double value will be returned.

11.3 Input File

Tabulated script files contain data (text) that is translated by the application (specifically, by its Command Interface) into scripts. The structure of a tabulated input file is the same for both comma-separated or tab delimited files. Figure 11.4 illustrates script data as displayed in a Microsoft Excel[®] .csv file or in a Microsoft Notepad[®] .txt file.

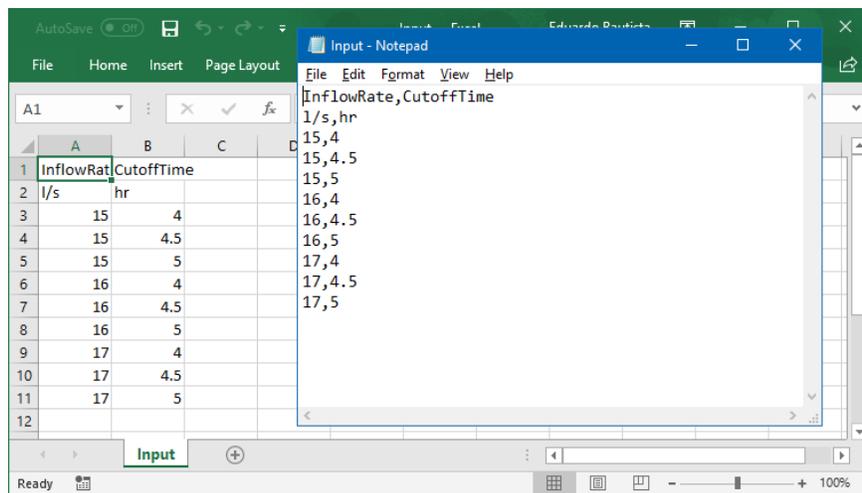


Figure 11.4: Tabulated script input file.

A tabulated script file can specify every single input required for a batch job, or only those inputs that will be varied. In the figure, only two variables are changing as part of the job - inflow rate and cutoff time. "InflowRate" and "CutoffTime" are script language

keywords. All other variables, such as slope, infiltration parameters, hydraulic resistance parameters, cutoff time, etc., do not change during the execution. The data for those variables can be entered through the tabulated script file (represented by a column of constant data), or through the user interface.

The first row in the tabulated script input file lists the keywords that will be specified during a batch job, one per column. The second row may contain data (variable values) or unit information. If all of the data is given in project units¹, units information is not needed and data can be entered starting in row 2. If the units of one or more variables are different from the project units, then they must be declared using the unit identifiers of Table 4.1. For example, if inflow rate is an input variable, and the project units for inflow rate are l/s, then those data will be assumed to be given in l/s unless the unit label indicates otherwise. Units can be declared in two ways. They can be included next to the variable name, enclosed in parentheses. Alternately, they can be specified in row 2, but without parentheses. If the latter approach is taken, data will be provided starting in row 3, as in the example. Only one unit declaration method can be used in a file.

A Command Line Script is built by the application by combining the keyword with its arguments - the value and the unit label (if given). The example of Figure 11.4 defines nine simulation runs. The first data row in the example is translated by the command interpreter into the following Command script:

- Length 500 ft
- InflowRate 1 cfs

The first script sets the inflow rate to 15 l/s while the second sets the cutoff time to 4 hr. After finding the last data item in a row, the application inserts a Command script that causes the simulation to execute (Simulation Run).

Keep in mind when writing Command tabulated scripts that the simulation engine will not be able to access data specified with Command scripts if other current configuration options, specified either through the user interface or by other Command scripts, do not provide a path to those data. For example, “InflowRate 1 cfs” will write a 15 l/s value to the Inflow Rate input box. This box can be viewed in the user interface, and thus accessible to the simulation, only when the **Inflow Method** is **Standard Hydrograph**. If the **Inflow Method** is set to **Surge**, then the simulation will operate on the value displayed in the surge Inflow Rate input box (SurgeInflowRate).

Also, several input controls trigger a procedure (an OnChange Event) when their value changes. That procedure changes the display of other configuration options and/or populates other input controls. An example is, of course, the System Type option buttons (Furrows vs.

¹Project units are the units set with the Edit/Units command. These are different than the units selected under User Preferences (which set the default units for new projects) or the units selected for individual input controls.

Basins/Borders). OnChange Events do not execute when values are written with scripts. As a result, input controls variables are not repopulated. This means that the values of variables associated with those controls must be specified with scripts. As an example, when the Green-Ampt infiltration function is selected, the **Soil Crop Properties** Tab displays a **Soil Texture** drop-down box. Selections with this control from the user interface changes the values of the Green-Ampt parameters. The command script “SoilTexture Clay” will change the value of the data structure associated with the Soil Texture input control, but will not force the input boxes for the Green-Ampt parameters to be repopulated. These inputs must be provided with scripts. The same problem occurs when defining infiltration with the NRCS intake families or the Time-Rated intake families.

Batch jobs are designed to test a range of conditions. Those conditions may, inadvertently, include scenarios that cause computational problems and trigger the messaging system of SRFR. For example, a simulation with advance-distance based cutoff will run into problems if the inflow rate is too small for the given infiltration conditions and field length. This situation will eventually cause the number of computational time steps to exceed a limit internal to the application. When this happens, SRFR stops the computations and offers the user the choice of increasing the number of time steps or end the simulation. The batch job will not proceed until the user responds. Problems of this type can arise even when cutoff is time based. When running large batch jobs, the SRFR messaging system needs to be disabled as described earlier (**Show Message on First Error**). Care must be exercised when running simulations in which cutoff is determined based on advance distance.

Lastly, Section 4.3.2 discussed the messaging system of WinSRFR. The application validates the inputs and will not allow a simulation, evaluation, operational analysis, or design scenario to execute if the data are incompatible. A scenario with incompatible data will cause the batch job to be terminated. Incompatibilities are more likely to occur when running batch jobs that include furrows and basins/border, as furrows have many more configuration options. In general, batch jobs should deal with only one type of system.

11.4 Output File

The tabulated script output file (Fig. 11.5) is used to build Command Queries for singled-valued results. These tabulated scripts are simpler than the input scripts. Only output keywords are required in row 1, one per column. Project units will be used on output and will be listed in the second row with requested results. Each simulation run will append a new row of results to the end of the file. The sample Input File described previously will produce nine rows of results added to this file. In Fig. 11.5, the tabulated script is used to extract the applied depth (D_{app}), the average infiltrated depth (D_{inf}), the runoff depth (D_{ro}), the deep percolation depth (D_{dp}), minimum infiltrated depth (D_{min}), low-quarter infiltrated depth (D_{lq}) and final advance time (TL). For documentation purposes, input data should also be included in the output file, especially when running multiple batch jobs. Inputs specified through the user interface can be included in the output file. In the example,

InflowRate and CutoffTime are displayed in the output file along with the results of interest.

The only variables that can be listed in a Query script file are those that will be available as the product of a simulation. They can be listed in any order because the scripts are simply reading data from the available data structures.

	InflowRate	CutoffTime	Dapp	Dinf	Dro	Ddp	Dmin	DIq	TL
	l/s	hr	m	m	m	m	m	m	hr
3	15	4	0.09	0.08	3.11E-03	0.01	0.04	0.06	3.58
4	15	4.5	0.1	0.09	0.01	0.01	0.05	0.07	3.58
5	15	5	0.11	0.1	0.01	0.02	0.06	0.08	3.58
6	16	4	0.09	0.09	0.01	0.01	0.05	0.07	3.11
7	16	4.5	0.1	0.09	0.01	0.02	0.06	0.08	3.11
8	16	5	0.12	0.1	0.01	0.02	0.07	0.08	3.11
9	17	4	0.1	0.09	0.01	0.01	0.06	0.07	2.76
10	17	4.5	0.11	0.1	0.01	0.02	0.07	0.08	2.76
11	17	5	0.12	0.1	0.02	0.02	0.08	0.09	2.76

Figure 11.5: Tabulated script output file, after execution of the batch job.

11.5 Extracting Series Results

Scripts can be used to extract computed time and space series. This information must be provided through the input file because the output file is reserved for singled-value results. Series data that can be extracted are:

Different types of hydrograph and profile data can be extracted, as will be noted in the following paragraphs. Series data are saved to individual .txt files, one for each combination

Table 11.1: Series results that can be extracted with Tabulated Scripts.

Keyword	Description
Advance	The advance trajectory (distance X vs. time T)
Recession	The recession trajectory (distance X vs. time T)
Infiltration	Final infiltration profile (infiltrated depth Z vs. distance X)
Hydrograph	A time series (a user-selected flow variable vs. time T)
Profile	A space series (a user-selected flow variable vs. distance X)

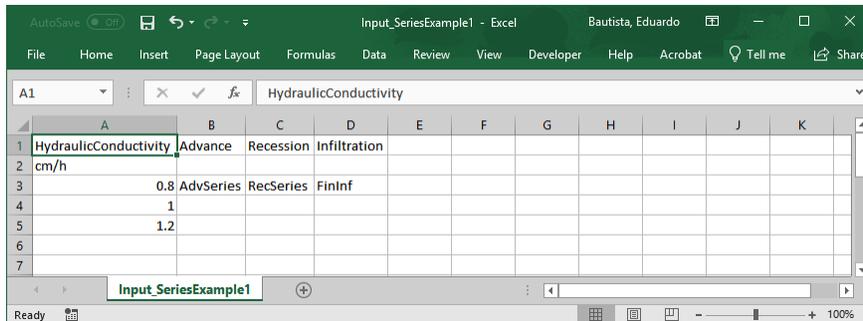


Figure 11.6: Series results that can be extracted with Tabulated Scripts.

of scenario and output series.

Figure 11.6 illustrates the structure of a tabulated script that extracts the advance and recession trajectories, and the final infiltration profile. The first row contains the names of variables that are modified during each simulation and the series type to be generated in the output. The series type is specified using the keywords of Table 11.1. When requesting series outputs, the units of the input variable must be given enclosed in parentheses next to the variable name. The single argument below the series output variable type is the base name of the output files that will be used to save the results. During execution of the batch job, a counter-generated number is appended to the base name. Hence, in the example, the batch job will generate three files each AdvSeries#.txt, ReceSeries#.txt, and InfSeries#.txt, where # is a number between 1 and 3. Series output units do not need to be specified as they are saved using project units.

A script that extracts a hydrograph or profile series requires two more arguments. The first is the name of the requested flow variable. Flow variable names recognized by the application are shown in Table 11.2. The second argument specifies either the location of a hydrograph, or the time for the requested profile data. This information is provided in row 1, next to the Hydrograph or Profile keyword. Figure 11.7 illustrates the structure of a script that extracts six series, three of them hydrographs and three profiles. The hydrographs are located at a distance of 50 m from the inlet, and the profiles are for 2 hours into the irrigation. The variables requested are flow area, infiltration area, and flow rate. Note that no space is left between the distance/time value and its units label. As in the example of Fig. 11.6, the first row of data is used to enter the base name of the text files used for output.

Table 11.2: Script flow variable identifiers

Variable name	Description
Y	Surface-flow depth
AY	Surface-flow area
Z	Infiltrated depth (volume per unit length per unit width)
AZ	Infiltrated volume per unit length
Zwp	Infiltrated depth adjusted by the wetted perimeter
Q	Flow rate
V	Flow velocity

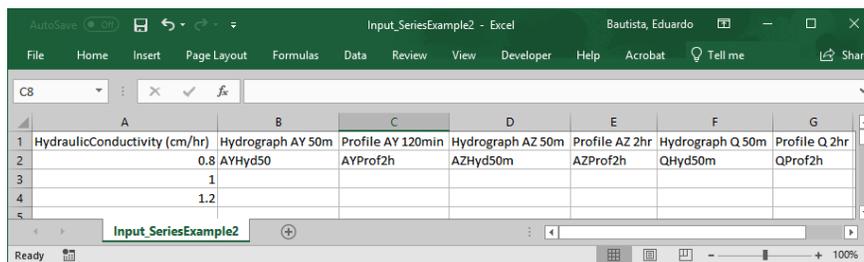


Figure 11.7: Structure of a tabulated script that extracts one hydrograph and one profile series.

11.6 Script Recorder Menu Commands

This section explains the Scripting menu commands offered by the Script Recorder. File commands are self-explanatory. There are two groups of Scripting commands, commands used to interact with scripts, and the second to view scripts. Commands used to interact with scripts are the following:

- *Record Script*: Use the Record Script menu item to start the Script Recorder's recording function. Use the WinSRFR user interface to edit the data. Each data change will generate a Command Line script that will be appended to the end of the Script Recorder screen. A sequence of scripts can be saved to a file. Stop Recording turns this function off.
- *Play Script*: A saved script file can be loaded in into the Script Recorder and then executed with the Play Script menu item.
- *Load Script*: The Load Script menu item creates equivalent Command Lines scripts based on the inputs currently available to the user interface. For example, *Load Script /System Geometry* loads the commands necessary to define the System Geometry setup currently in memory.

The record, play, and load scripts functions were originally developed to support the development of applications intended to interact with the WinSRFR user interface. Tabulated scripts and the availability of the SRFR 5 API now make those functions of limited value for programmers. However, they can be used to help in learning the scripting language. They can also be used to apply common changes to a series of related scenarios in a project file.

Scripting commands used to view the Script Language are self explanatory:

- *View Command Language*
- *View Query Language*

The scripting language is updated dynamically depending on the data structures required by a particular configuration (Command Language) or the data structures generated by a successful simulation (Query language). Hence, slightly different subsets of the language will be displayed by the Script Recorder depending on how the system is configured.

11.7 Examples

The file *Test_batchSimulations.srfr* contains two scenarios that illustrate the use of batch simulations. The scenario Simulation 1 simulates a 100 m long free-draining border with infiltration given by the Green-Ampt equation. The scenario is used to test different combinations of inflow rate and cutoff time, as shown in Fig. 11.4. In the Run Multiple Simulations dialog form, enter Input.csv and Output.csv as, respectively, the input and output files. Alternatively, you can use the .txt files of the same name. The requested outputs are those

shown in Fig. 11.5. The first two columns in the output file are the specified inflow rate and cutoff time. These two values are specified using the command labels as in the input file (see Figs. 11.4 and 11.5). Note that some variables, such as inflow rate and cutoff time, can be outputs of the simulation and that query variables need to be used to retrieve that information. An example is when cutoff is specified based on advance distance.

The scenario Simulation 2 illustrates how to retrieve time and spaces series data. The scenario is essentially the same as Simulation 1, but in this case the hydraulic conductivity is variable for a fixed inflow rate and cutoff time. Use Simulation 2 first in combination with the *Input_SeriesExample1.csv* and *Output_SeriesExample1.csv* files. The input file was previously illustrated in Fig. 11.6. All outputs will be stored in the same directory as the project and .csv files. Use the Simulation 2 scenario next in in combination with the *Input_SeriesExample2.csv* and *Output_SeriesExample1.csv* files. This will retrieve hydrograph and profile series information, as illustrated in Fig. 11.7.

Part IV

Bibliography and Appendices

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APPENDIX A

SRFR GOVERNING EQUATIONS

Surface flow in surface irrigation can be modeled with modified versions of the Saint Venant (Barré de Saint-Venant, 1871) equations, which describe continuity and momentum for one-dimensional unsteady open-channel flow. In differential form, these equations are (Strelkoff and Clemmens, 2007):

$$\frac{\partial A_y}{\partial t} + \frac{\partial Q}{\partial x} + \frac{\partial A_z}{\partial t} = 0 \quad (\text{A.1})$$

$$\left[\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left(\frac{Q^2}{A_y} \right) + \frac{v}{2} \frac{\partial A_z}{\partial t} \right] + gA_y \left[\frac{\partial y}{\partial x} - S_0 + S_f \right] = 0 \quad (\text{A.2})$$

Equation (A.1) expresses the principles of conservation of mass, and states that the time t [T] rate of change in the surface volume per unit length A_y [L^3/L] is a function of the rate of change with distance x [L] of water flux Q [L^3/T] and the time rate of change of water loss due to infiltration A_z [$\text{L}^3/\text{L}/\text{T}$]. A_z is the infiltration component, which can be represented with one of several available equations. Conservation of momentum is expressed by Eq. (A.2), which states that the time rate of change of momentum (represented by the term $\partial Q/\partial t$) is a function of the distance rate of change of momentum flux ($\partial/\partial x \cdot [Q^2/A_y]$), the sum of forces acting on the flow, and momentum sinks. The forces are the gradient in hydrostatic pressure ($gA_y \partial y/\partial x$), the weight component of the water in the direction of flow ($gA_y S_0$), and frictional resistance by the soil surface and vegetation ($gA_y S_f$), in which g is the acceleration of gravity [L/T^2], y the flow depth [L], S_0 [-] the field bottom slope, and S_f [-] the friction slope. The sink term represents the loss of momentum due to infiltration, with v = flow velocity [L/T] (Strelkoff and Clemmens (2007)). Eq. A.2 is written in non-divergent form, meaning that under some conditions, it fails to properly conserve momentum.

Equations (A.1) and (A.2) constitute a coupled system of hyperbolic, non-linear differential equations. With hyperbolic equations, computations start with known values for the dependent variables at time zero, and the solution then propagates forward in time along paths in the $x - t$ plane known as characteristics. Since the speed of propagation along the characteristics is finite, the solution at any point in the computational domain depends on a finite region bounded by characteristics intersecting at that point. Equations (A.1) and (A.2) are associated with two sets of characteristics, one with a positive slope (i.e. positive speed), while the other can have a negative, zero, or positive slope. Information entering the computational domain through a positive characteristic can only travel in the positive (downstream) direction, while information entering through a negative characteristic travels upstream. This allows modeling of waves reflecting off the downstream boundary. The overall behavior of hyperbolic equations need to be taken into account when developing numerical solutions in order to prevent computations from becoming unstable or producing inaccurate results. Numerical schemes based on the method of characteristics, explicit finite differences, implicit finite differences, and finite volumes have been proposed for solving the unsteady open-channel flow equations.

Under typical irrigation conditions, where flow velocities and the Froude number of the flow are small (typically less than 0.2), the zero-inertia model can produce solutions similar to those computed with the hydrodynamic model while avoiding some computational problems (Strelkoff and Clemmens, 2007). The zero-inertia model neglects the inertial terms in the momentum equation (as well as the infiltration contribution) and, thus, replaces Eq.(A.2) with

$$gA_y \left[\frac{\partial y}{\partial x} - S_0 + S_f \right] = 0 \quad (\text{A.3})$$

Equations (A.1) and (A.3) represent a parabolic system of differential equations. As with hyperbolic equations, information propagates along characteristic paths, but the speed of propagation is infinite. Hence, the domain of dependence at a point in the $x-t$ plane is the entire computational domain bounded by the current time line. Because of this property, parabolic equations can be solved efficiently and with fewer computational problems than hyperbolic ones with implicit finite difference schemes. Those schemes make all computational nodes at the current time line dependent on each other. Since characteristic paths emanate from both boundaries, as in the hydrodynamic model, the zero-inertia equations can model the reflection of waves.

Numerical solutions of Eqs. (A.1) and (A.3) can produce artificial oscillations in the computed depth and discharge profiles when the field bottom slope is relatively large, as the surface profile is relatively uniform but experiences very rapid changes near the tip of the advancing wave. Under those conditions, since the weight of the fluid is essentially in balance with the frictional resistance, the pressure gradient term is small and can be neglected. This reduces Eq. (A.2) to

$$S_f = S_0 \quad (\text{A.4})$$

which implies normal flow depth at any distance x as a function of the local Q . This condition is more easily met with relatively large slopes and irrigation times.

Equation (A.1) in combination with (A.4) yields the kinematic wave model (Strelkoff and Clemmens, 2007). It consists of a single hyperbolic partial differential equation with one dependent variable. Since the model is associated with positive characteristics only, it can only model waves that travel in the downstream direction and boundary conditions can only be specified at the upstream end of the field. As a result, the kinematic wave model cannot be used with blocked-end systems. It cannot be used either when the bottom slope is zero or adverse on any field segment, as normal flow cannot be attained.

For a more complete description of the governing equations of surface irrigation see Walker and Skogerboe (1987) and Strelkoff and Clemmens (2007). Implementation of the zero-inertia and kinematic wave models in the SRFR 5 modeling system is discussed in Bautista et al. (2016a).

APPENDIX B

ESTIMATION OF INFILTRATION PARAMETERS WITH VOLUME BALANCE

B.1 Principles of Volume Balance Analysis

In volume balance analysis, the infiltrated volume V_z at time t_i is calculated as the residual:

$$V_z(t_i) = V_{in}(t_i) - V_{ro}(t_i) - V_y(t_i) \quad (\text{B.1})$$

in which: V_{in} = inflow volume; V_y = surface storage volume, and; V_{ro} = runoff volume. Except when applied at the conclusion of an irrigation, a key challenge to the application of Eq. (B.1) is the determination of V_y . The more common approach is to estimate V_y hydraulically, as

$$V_y = \sigma_y \cdot A_y(0) \cdot x_A \quad (\text{B.2})$$

in which σ_y = dimensionless surface shape factor, $0.5 < \sigma_y < 1.0$; $A_y(0)$ = upstream flow area [L^2], and; x_A = stream advance distance [L]. All of these variables are functions of time. They are also a function of hydraulic resistance, which typically is also unknown. Hence, accurate estimates of the roughness coefficient are needed to accurately estimate V_y with Eq. B.2. An alternative to the use of Eq. B.2 is to determine V_y from measured water surface profiles. This approach is mostly used for research purposes because of the difficulties of obtaining those measurements. Both methods for the determination of V_y are used by the Event Analysis World.

The estimation problem attempts to match volumes calculated with Eq. B.1, i.e. the measured volumes, with predicted values V_z^* . The latter are computed by integrating the infiltration profile over the length of wetted field:

$$V_z(t_i) \approx V_z^*(t_i) = \int_0^{x_A(t_i)} A_z(\tau_x, \alpha_1, \alpha_2, \dots, \alpha_n) ds \quad (\text{B.3})$$

Here, $A_z(s)$ = a functional relationship for the infiltration volume per unit length; τ = intake opportunity time (total time t_i minus the advance time to distance x , t_x), and $x_A(t)$ is as previously defined, and $\alpha_1, \alpha_2, \dots, \alpha_n$ are the unknown, spatially-averaged parameters of $A_z(s)$, which we are trying to estimate. The number of parameters depends on the user-selected A_z . Numerical methods need to be used to find an approximate solution to Eq. B.3 for an arbitrary function A_z . Approximate analytical solutions are also available, but only for empirical infiltration equations dependent on opportunity time only. Which method is used depends on the particular estimation method.

In principle, as many volume balance equations are needed as the number unknown parameters to solve the estimation problem. However, because of infiltration spatial variability and of the uncertainty of the measured V_z values, different solutions will emerge for different volume balance calculation times. Hence, estimation techniques often formulate more equations than unknowns, and then minimize the difference between observations and predictions. This is why in Eq. B.3, V_z^* is only an approximation to V_z .

For additional details, see Strelkoff et al. (2009), Bautista and Schlegel (2017a), and Bautista and Schlegel (2017b).

B.2 Modifications to the Two-Point Method

WinSRFR 5.1 introduces changes to the implementation of the two-point analysis with respect to previous versions. As originally developed Elliott and Walker, 1982, the method calculates V_y with Eq. B.2, using a constant $\sigma_y = 0.77$. The well-known power-advance integral Strelkoff and Clemmens, 2007 is used to approximate Eq.B.3 analytically. That solution assumes that infiltration at any distance is a function of opportunity time only and that the stream advances down the field following an empirical power law of time. The integral simplifies to

$$V_z^* = (\sigma_{z1}(a, r) \cdot K\tau^a + \sigma_{z2}(r) \cdot B\tau) \cdot x_A \quad (\text{B.4})$$

In this expression $\sigma_{z1}(a, r)$ and $\sigma_{z2}(r)$ are subsurface shape factors, constant with time, both in the range 0.5 to 1.0. Both are functions of the exponent of the advance power law:

$$x_A = p \cdot t^r \quad (\text{B.5})$$

where p [L/T^r] and r [\cdot] are parameters fitted from field data. $\sigma_{z1}(a, r)$ also depends on the infiltration exponent a , to be discussed in Section 5.4. Simulation studies have shown that the shape factors σ_y, σ_{z1} and σ_{z2} are not constant with time and, furthermore, that they depend on irrigation systems properties, including the unknown infiltration parameters. WinSRFR 5.1 incorporates procedures for refining the shape factor estimates (Bautista et al., 2012a; Bautista et al., 2012b) and assumes that inputs will be adjusted by trial-and-error with

simulation support to better match simulation results to the measured runoff hydrograph (Bautista et al., 2009b), if one is available.

INFILTRATION TECHNICAL NOTES

C.1 Characteristic Infiltration Time

The characteristic time may be suggested by experience on a particular field. For example, an irrigator may typically target an application depth of 75 mm (3 in) and may know from experience that, approximately, 6 hours of ponding are needed at the point of minimum infiltration to infiltrate that depth. Likewise, the exponent a can be gleaned from previous experience with soils in the area. The characteristic time concept is most useful for sensitivity analyses, when testing a solution to potential variations in infiltration, with the range of variation defined by τ_c .

C.2 Time-Rated Intake Families

Merriam and Clemmens (1985) analyzed infiltration data collected with ring infiltrometers in border systems. From those data, they developed a relationship for the calculation of the exponent of the Time-Rated Intake Families:

$$a_{mc} = 0.675 - 0.2125 \cdot \log_{10}(\tau_{100}) \quad (\text{C.1})$$

In which τ_{100} is the opportunity time needed to infiltrate 100 mm. The constant k_{mc} can then be calculated from the Kostiakov equation, with the units of k_{mc} depending on those of τ_{100}

$$k_{mc} = \frac{100}{\tau_{100}^{a_{mc}}} \quad (\text{C.2})$$

Since the data set used to develop Eq. C.1 did not include cracking soils, the Time-Rated

Intake Families should not be used with those types of soils. Also, since the concept was developed for one-dimensional infiltration, this option is offered only for border/basin systems.

C.3 NRCS Empirical Wetted-Perimeter for Furrow Infiltration Calculations

The NRCS method for computing furrow infiltration uses Eq. 5.18 to determine the wetted perimeter, which is shown again next:

$$WP_{IF} = WP_g(Q_0, n, S_0) + \Delta WP$$

This section discusses the limitations of this approach. First, to simplify calculations, the method developers proposed an approximate formula to calculate the geometric wetted perimeter WP_g for typical furrow cross-sections:

$$WP_g = c_1 \left(\frac{Q_{in} \cdot n}{\sqrt{S_0}} \right)^{0.4247} + c_2 \quad (C.3)$$

In this expression, c_1 and c_2 are constants that depend on the system of units, S_0 is the field bottom slope, and other variables have been previously defined. Equation (C.3) was developed from trapezoidal cross-sectional data, with bottom widths between 0.06 and 0.15 m (2.4 and 6 in), and side slopes (H/V) between 1:1 and 2:1 (USDA-SCS, 1984). Therefore, it computes the same wetted perimeter value for any geometry with a given Q_{in} , S_0 , and Manning n . Since the actual perimeter can vary substantially within the range of conditions used to develop the expression (Perea et al., 2003), larger errors can be expected if used outside the above-mentioned ranges.

Equation (C.3) was developed primarily for sloping furrows and tends to under predict at small slopes and over predict with large slopes. Since the equation cannot be applied when $S_0 = 0$, the developers replaced S_0 with an estimate of the friction slope S_f (USDA-SCS, 1984). This leads to a mathematical discontinuity for the wetted perimeter at $S_0 = 0$. The equation is inapplicable with negative slopes which can be encountered with drainback systems.

If the inflow rate is specified as a tabulated hydrograph, WinSRFR interprets Q_{in} as the average discharge rate over the total period of inflow and that value is used in combination with Eq. (C.3). If the inflow rate is specified with the standard hydrograph option in combination cut-back, then Eq. (C.3) is applied considering the flows before and after cutback, as in the original USDA-SCS (1984) publication. This means that different WP_g values can be generated with identical cutback scenarios, depending on how the inflow is specified (tabulated vs. standard with cutback).

Lastly, the constant factor ΔWP was developed from field measurements and without the benefit of simulation studies based on soil physics. Infiltration simulation models based on the two- and three-dimensional Richards equation have become available in the last couple

of decades. Perea et al. (2003) showed that NRCS furrow infiltration method can match infiltration predictions generated with the HYDRUS-2D (Šejna et al., 2012) program, at least for limited times. However, they also found that different values of ΔWP , substantially smaller than the value adopted in USDA-SCS (1984), were needed for the range of soil conditions that they examined.

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