ARID-LAND AGRICULTURAL RESEARCH CENTER

WinSRFR 3.1 User Manual

WinSRFR 3.1 Help & Manual

Surface Irrigation Analysis, Design & Simulation

by ALARC

WinSRFR is produced by:

U.S. Department of Agriculture
Agricultural Research Service

Arid-Land Agricultural Research Center
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1   Welcome to WinSRFR 3.1

WinSRFR is an integrated hydraulic analysis application for surface irrigation systems that combines a simulation engine with tools for irrigation system evaluation, design, and operational analysis. Intended users are irrigation specialists, university extension agents and researchers, consultants, and farmers with moderate to advanced knowledge of surface irrigation hydraulics.

WinSRFR History

WinSRFR is the successor to irrigation modeling software developed over the past 20+ years by the USDA-Agricultural Research Service, namely:

SRFR: One dimensional simulation of basin, border, and furrow irrigation
BASIN: Level-Basin irrigation design and operations
BORDER: Sloping-Border irrigation design and operations

WinSRFR 1.1, released Sept. 2006, integrated the functionality of these legacy DOS programs into a single Windows application. WinSRFR 1.2, released May 2007, addressed several issues & bugs in the first release.

WinSRFR 2.1, released Dec. 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

What's New in WinSRFR 3.1?

- New Physical Design and Operations Analysis procedures based on volume balance solutions tuned with zero-inertia simulation results. The new procedures:
  - Replace the existing solutions for borders and basins, based on static databases of pre-computed unsteady flow solutions
  - Expand the range of options used to specify infiltration characteristics for physical design and operational analysis problems
  - Expand the physical design and operational analysis functionality to included close-ended borders and furrows, level furrows, and furrows with cutback

- Erosion simulation
- THIS FEATURE HAS BEEN DISABLED FOR VERSION 3.1
- Advanced feature in the Simulation World applicable mostly to systems with relatively steep slope
- The Evaluation World also offers a rudimentary procedure for estimating erosion parameters from field measurements of sediment concentration

- Simulation engine improvements
  - Problems have been corrected in the simulation engine that affected recession calculations

- New user-interface features
  - Additional User Preferences options for configuring X-Y graphs and contour plots
  - Additional Data Comparison options for calculation of Performance Indicators and Goodness-of-Fit metrics

○ Hydraulic Summary graph added to the Physical Design and Operations Analysis Worlds; the graph allows the user to compare volume balance results with zero-inertia simulation results at the selected solution point

○ Dmin (Dlq) = Dreq graph added to the Operations Analysis World. This graph allows the user to quickly view all solutions (combinations of discharge and cutoff time) satisfying the irrigation requirement (Dmin = Dreq or Dlq = Dreq) and their impact on application efficiency.

First Look at WinSRFR

Shown here is the Project Management Window, the first window to display when WinSRFR starts.
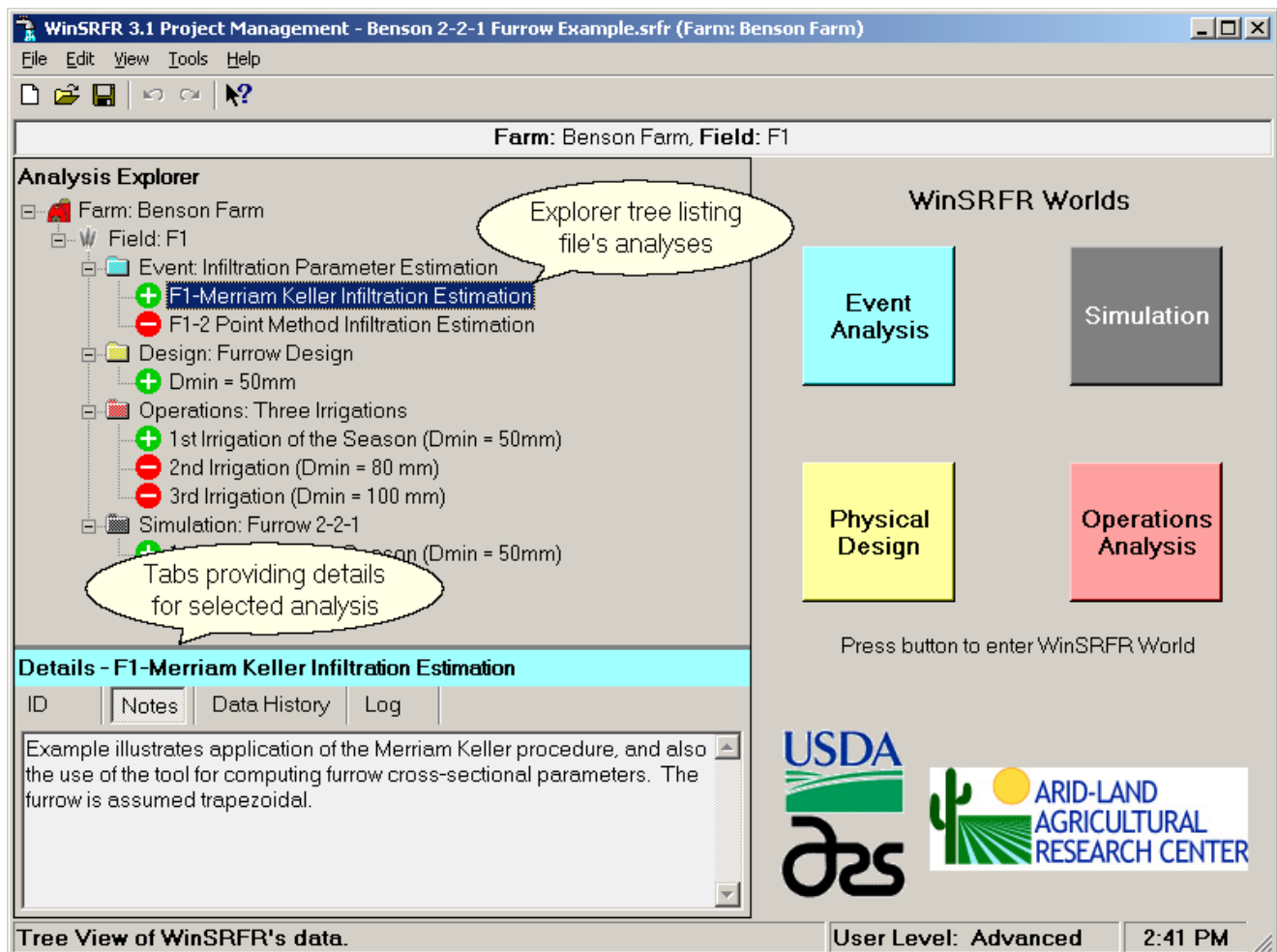
WinSRFR Project Management Window

WinSRFR provides its functionality in four color-coded Worlds:

Event Analysis World	- Irrigation event analysis and parameter estimation functions
Physical Design World	- Design functions for optimizing the physical layout of a field
Operations Analysis World	- Operations functions for optimizing irrigations
Simulation World	- SRFR's simulation functions for testing and sensitivity analysis
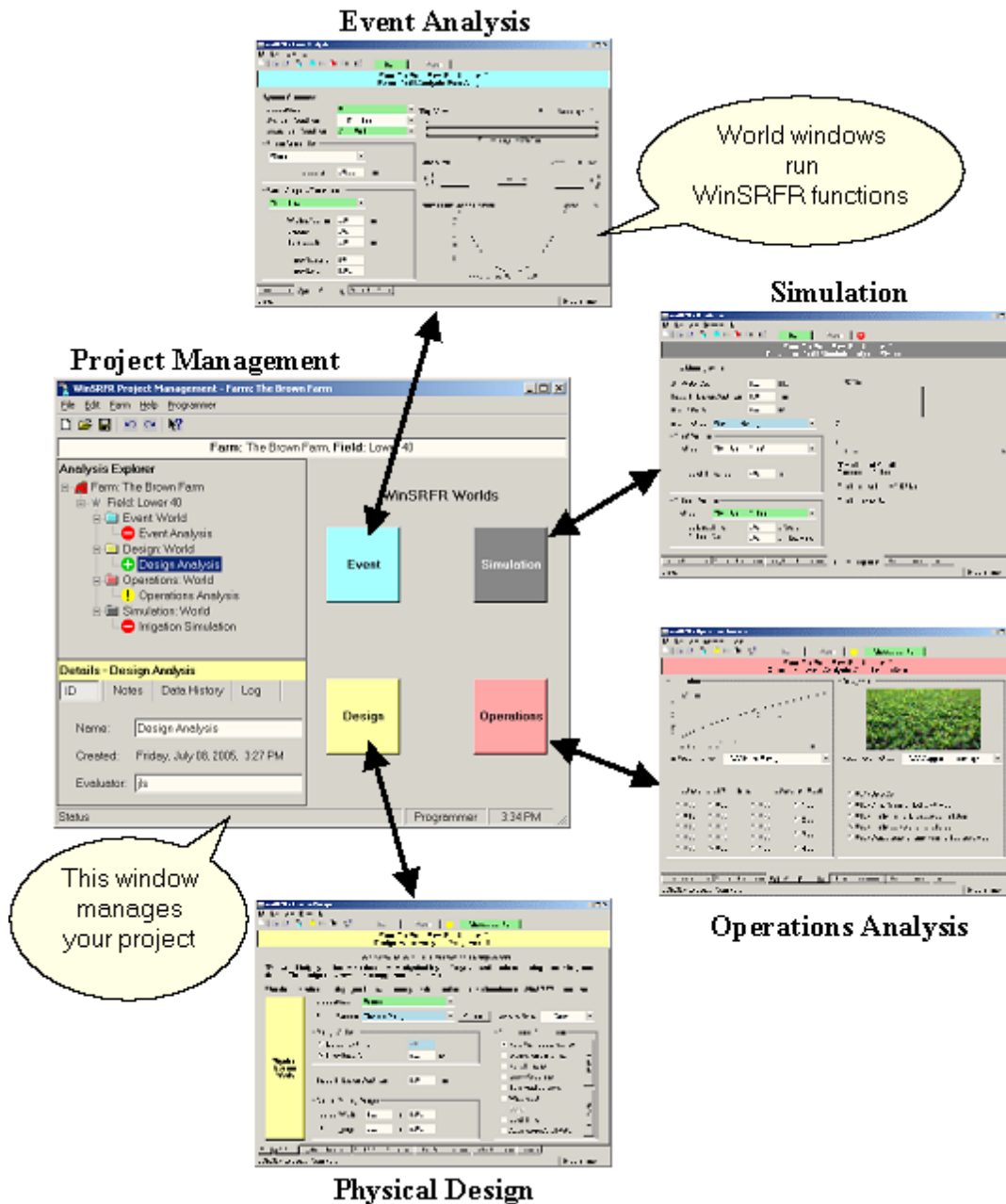
Figure 1.2 - WinSRFR's Four Worlds of Functionality

1.1   Getting Started

WinSRFR is developed and supported by:

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

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1.1.1   Operating System and Hardware Requirements

WinSRFR is a Windows application implemented using Microsoft's .NET Framework 1.1. WinSRFR requires the following minimally configured PC for acceptable operation:

Supported Operating Systems

     Windows XP
     Windows 2000
     Windows Vista

Additional Software Requirements

     Microsoft's .NET Framework 1.1 (Installed by WinSRFR Installer if necessary)
     WinSRFR has not been tested with .NET Framework versions 2.0 or later

Storage Requirements

     20 MB for the program. Project files can each be several MB in size.

Monitor

     800 x 600 or larger resolution

All windows and dialog boxes provided by WinSRFR fit within an 800 by 600 pixel rectangle. This allows WinSRFR to be run on monitors capable of displaying 800 by 600 resolution or better. Most windows can be resized and, when operated in the Graphics Only view mode, all graphical results automatically scale to fit the available space.

1.1.2   Installation/Uninstallation

Installation

WinSRFR 3.1 must be installed using the installation program **AlarcWinSrfr31Setup.exe**, which will decompress all needed files, register libraries with the Windows operating system and create needed directories. By default, the program will install under the C:/Program Files folder and create a /USDA/WinSRFR 3.1 subdirectory. Other USDA-ARS developed software may also install under the folder /USDA.

Uninstallation

The program must be uninstalled using the Add/Remove Programs command under the Windows Control Panel, in order to correctly unregister the application and all its associated files.

1.1.3   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. When this option is selected several restrictions are imposed upon the application. For example, only system colors selectable through Control Panel or colors set by the user may be used by the application.

- 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 part of the application has the focus. This requirement also enables 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.

All windows and dialog boxes provided by WinSRFR fit within an 800 by 600 pixel rectangle. This allows WinSRFR to be run on all monitors capable of displaying 800 by 600 resolution or better. Most windows can be resized and, when operated in the Graphics Only view mode, all result graphs automatically scale to fit the available space.

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

1.1.4   Credits and Acknowledgements

Mr. J.L. Schlegel was the lead software developer for WinSRFR. Mr. D. Bourne and Mr. J. Cooperwood were software developers for the project.

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, Mr. B.V. Schmidt, Mr. E. J. Slosky, and M. Shatanawi.

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.

USDA-NRCS provided significant input and feedback during the development of this software package. In particular, USDA-ARS acknowledges the contributions of Mr. Clarence Prestwich, Irrigation Specialist, National Water & Climate Center, USDA-NRCS.

1.1.5   Disclaimer

The software can be used to analyze both practical and theoretical irrigation problems. Analytical procedures are based on mathematical representations of irrigation systems, using a combination of physical principles and empirical relationships. Users need to interpret results judiciously, however, as 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.

1.2 Overview of WinSRFR's Functionality

WinSRFR organization and functionality are based on the analytical process typically followed when examining surface irrigation hydraulic problems.

The first step in the process is an evaluation of current performance. The analysis, based on field-measured data, determines the fate of the irrigation water: how much water was applied, how much contributed to satisfy the requirements, e.g., to replace the soil water deficit, and how much was lost by deep percolation and runoff. For these studies, data from one or more observed irrigation events needs to be organized, represented graphically, and summarized. The evaluation may also be used to generate estimates of infiltration parameters, needed to determine infiltration distribution, and those parameter values have to be validated. The analysis generates performance measures and helps identify operational and/or design factors that may be affecting performance.

The next step in the process is a comparison of alternative operational scenarios. In the past, simulation tools or procedures such as those described in the NRCS design guides have been used, where the analyst needs to predict the irrigation system's performance as a function of operational variables (discharge rate, application time). Doing this by trial-and-error across a range of values for the variables of interest can be a tedious task. This version of WinSRFR allows one to determine performance over a wide range of conditions very quickly. The analysis may produce an operational recommendation (for the assumed average field conditions for infiltration, roughness, and target application depth) or may suggest the need for an alternative design.

In the latter case, the analysis may examine the performance under an alternative layout. This may include changes in field slope (if soil conditions allow) and field dimensions (length and width). Again, simulation or accepted engineering procedures need to be applied to perform these types of analyses, based on expected average field conditions. WinSRFR also provides design solutions over a range of conditions very quickly.

During any one of these procedures (evaluation, operational analysis or design), WinSRFR determines advance, recession, and the distribution of infiltrated water for the user specified conditions for comparison. Or the user can independently run a simulation.

For both operational and design studies, and because field conditions vary during the irrigation season, sensitivity analyses need to be conducted to assess how performance will degrade with likely variations in system inputs relative to the design values. If performance proves too sensitive, then additional design or operational analysis will have to conducted, to identify an alternative recommendation (design or operation) that is more robust (i.e., a recommendation that may attain a lower performance level but that may be less sensitive to possible deviations in field conditions from the design values). This functionality has yet to be added to WinSRFR.

Given this process, WinSRFR was designed with two important organizational features. First, WinSRFR has four major defined functionalities. These functionalities, referred to as Worlds in the software, are Event Analysis, Operation Analysis, Physical Design, and Simulation. These functions are explained in later sections. The second organizational feature is that scenarios run with these functions are stored in separate data folders. This structure organizes the data into logical groups and allows outputs generated in one World to be used as inputs in a different World (as well as using the same inputs in different Worlds).

This section summarizes the hydraulic analysis capabilities of WinSRFR's Event Analysis, Physical Design, Operation Analysis and Simulation Worlds. Detailed technical descriptions of the procedures employed in WinSRFR are provided in various technical references, several of which are found in the Technical Background section.

1.2.1   Event Analysis

Procedures in the Event Analysis world are used to evaluate the performance of irrigation events from field measured data and to estimate infiltration parameters needed for evaluation, simulation, physical design, and operational analysis. These procedures use physical principles, particularly a mass balance, to determine the disposition of the irrigation water. These evaluation procedures currently are provided:

- Infiltration profile analysis from probe penetration data
- Merriam-Keller analysis of advance and recession data (Merriam and Keller, 1980)
- Elliot and Walker's (1982) two-point method analysis of advance data
- Erosion Parameter Estimation

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, and is applicable in heavy to medium-textured soils. The water penetration depth is used to estimate the post-irrigation depth of infiltration water d contributing to the irrigation target, D_{req}. D_{req} is calculated considering the depth of water needed to replace the root zone soil water deficit and water needed to meet the leaching and other 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. Since infiltration parameters are not determined with this procedure, insufficient information is provided for further analysis in WinSRFR. (That is, the user cannot perform operation evaluation, design, or simulation). Thus it is not useful for providing quantitative recommendations for improvement.

The **Merriam-Keller procedure** is a method for estimating the infiltration depth profile from a post-irrigation mass balance. The method can be applied to basins, borders, and furrows. The method matches the observed infiltration volume, calculated from the difference of measured inflow and outflow, with the numerical integral of the post-irrigation longitudinal infiltration depth profile. Infiltration depth at discrete points along the field is calculated from observed intake opportunity times, computed from the measured advance and recession times. Originally, the method used the resulting mass balance relationship to solve for the constant k of the Kostiakov infiltration, with the exponent a given from ring infiltrometer measurements or experience. WinSRFR implements the Merriam-Keller procedure for a variety of infiltration equations. Since the method solves for infiltrated volume at the end of irrigation, only one infiltration coefficient (or family) can be determined. WinSRFR typically solves for k. Other terms used with the other equations have to be entered by the user (e.g., the steady state term b and the storage term c). In addition to the outputs described above, the analysis produces an estimate of the field's infiltration function. The accuracy of the estimated function can be verified via simulation. A trial-and-error approach needs to be used to determine the combination of parameters (the given a, b, c and the resulting k) that will most closely reproduce the observed advance and recession trajectories, and the observed runoff hydrograph, if one was measured.

Elliott and Walker's Two-Point Method is a procedure for estimating the k and a parameters of the extended Kostiakov equation from two advance time observations. The method was developed for sloping furrow irrigation. WinSRFR's implementation of the method allows the user to apply it to sloping borders as well. The method uses the two observed advance times to set up two mass balance equations. Such equations require estimates of the volume of water stored in the surface during advance. The original approach used normal depth at the upstream end and a surface shape factor. Normal depth is not applicable for shallow slopes, so WinSRFR uses the zero-inertia representative upstream depth (discussed later). The analysis does not require a measured hydrograph, but at least an estimate of the Extended Kostiakov steady state infiltration rate term b is

needed in order to calculate k and a (c is assumed equal to zero). Inputs required by the analysis are; a) the measured inflow; b) advance times to two distances along the field (half the field length and full field length are strongly recommended); c) the measured outflow or an estimate of the steady state infiltration rate; d) an estimate of the Manning roughness coefficient, which is used to calculate normal depth; and e) for furrows, a description of the furrow cross sectional area (side slope and bottom width for trapezoidal furrows, power constant and exponent for parabolic shaped furrows). Outputs of the analysis, as indicated before, are k and a. If runoff measurements are available, then the function can be validated via simulation. In such cases, a trial-and-error approach is recommended to find the function that will best match the observed irrigation event, based on adjusting the value of b. A new approach has been developed based on a modified Philip Equation, where a = ½ and the two point method solves for k and c. For version 3.1, this method has not yet been programmed.

Erosion Parameter Estimation: THIS FEATURE HAS BEEN DISABLED FOR VERSION 3.1. An additional procedure is available for estimating a field's erodibility parameters used when simulating erosion. The current method requires input of an erosion concentration at the quarter point of the field at a given time from the beginning of irrigation. (Future version will hopefully be more flexible in the selection of field measured values). To use this option, the user must first determine infiltration from one of the evaluation procedures, or must enter known infiltration parameter values.

1.2.2   Simulation

Hydraulic Simulation

SRFR solves the unsteady open-channel flow equations coupled with empirical equations describing infiltration and channel roughness. The partial differential equations of unsteady open-channel flow represent the physical principles of conservation of mass and momentum. Given the relatively low velocities and Froude numbers that characterize surface irrigation flows, SRFR uses simplified forms of the momentum equation. Such a modeling approach is nearly as accurate as using the full unsteady equations, if used under the right conditions, but is more robust and computationally faster. The zero-inertia (equilibrium) version accounts only for pressure gradient, friction, and gravitational forces acting on the flow. This form of the equations can be applied to all practical field conditions. The kinematic-wave version ignores the pressure gradient force and assumes that frictional forces are in balance with gravitational forces, i.e., that flow is at normal depth everywhere. Such an assumption is reasonable with relatively large slopes and only when there are no backwater effects (i.e., is applicable only to open-ended systems). SRFR automatically determines which model to use under the given conditions, but the user can override the kinematic-wave option (i.e., the user can use the zero-inertia option in cases where the kinematic-wave approach is applicable, but cannot specify the kinematic-wave option it that method is inapplicable).

Infiltration can be calculated from physical principles and surface irrigation models have been proposed that couple physical infiltration equations to the unsteady flow equations. Those models are mathematically delicate and presently impractical except for fundamental scientific studies. At this time, SRFR uses empirical infiltration relationships, with the specific functional form selected by the user. The basic Kostiakov power law and some variations are provided by SRFR.

SRFR can be configured to model basins, borders, and furrows, but it is a one-dimensional simulation model -- it assumes that all flow characteristics vary only with distance along the main direction of flow (longitudinal distance) and time, but not across the field width. For borders and basins, the model is applicable to situations where field properties and system inputs vary negligibly across the field width, e.g., negligible cross slope, uniform infiltration and roughness, and uniform inflow. For furrows, simulations consider only a single furrow and, therefore, neighboring furrows are assumed identical. Any variation in properties from furrow to furrow must be modeled separately.

The results of a simulation, like those of an actual run in the field, depend on the hydraulic properties of the soil and crop (infiltration and roughness), the geometrical configuration of the system (length, cross-section, slopes, etc.), and system operation (flow rates, duration). Performance estimates depend also on the target infiltration depth for the irrigation. Users can assign constant field properties like the infiltration characteristics and roughness, bottom slopes, and furrow cross sections, or can prescribe variations in these properties with distance along the flow direction, and with inundation time. The user needs to specify all these inputs for the simulation to be performed. Simulation results include the advance and recession curves, flow and depth hydrographs at specified locations, water surface profiles at specified times, and a variety of performance measures such as application efficiency, distribution uniformity, and adequacy of the irrigation.

Erosion Simulation

THIS FEATURE HAS BEEN DISABLED FOR VERSION 3.1. Erosion simulation, available for Advanced Users only, enables calculation and display of soil detachment, transport, and deposition in response to the simulated field flow and soil properties.

1.2.3   Physical Design

Design involves finding one or more field configurations (length and/or width) that will yield acceptable levels of performance for the given field slope, soil and crop characteristics and available inflow. In WinSRFR, simple volume-balance procedures are used to compute advance, and recession is computed with a combination of volume balance and empirical procedures. From this performance contours are computed for a range of length and width combination (or length versus flow rate if the width is fixed). WinSRFR uses simulations to tune the empirical procedures so that the empirical results match the WinSRFR simulation results at a calibration point. The contour maps of performance are very accurate at the calibration point and drift away as one moves away from this point. This calibration point is initially selected by WinSRFR based on the range of conditions specified by the user. However, the user can alter this point and recomputed the performance contours. The methods works very well for sloping furrows and border strips with run off. Solutions tend to deviate more for level basin and low-gradient border strips. The user can evaluate the quality of this tuning by choosing a solution point within the contour map and comparing the empirical design results with simulation.

For level-basin systems, which have zero slope and no runoff, the design is constrained by theoretical performance limits: for a given set of conditions, there is a field length beyond which impractically large inflow rates coupled with very small times of cutoff would be required to maintain a target performance level. This combination would require streams to "coast" (advance without inflow) for so long after cutoff that reaching the end of the basin becomes problematic, with even slight deviations from the assumed infiltration and roughness. To demonstrate this limit, performance contour for level basins are not given if the stream is cut off before 85% of the field length. No limit is provided for low-gradient blocked-end border, but resulting performance contours can be problematic, if cutoff occurs well before advance is completed.

1.2.4   Operational Analysis

Operational analysis is similar to design analysis, except that the configuration is fixed while operational variables (discharge and cutoff time/distance) are unknown. Thus, the analysis requires simulation results from different combinations of the operational variables The same procedures described in design are used here. Selection of the calibration point is more difficult for operations since there is typically a large portion of the graph that is not feasible due to either low flow rate or small application time. Overlay of application efficiency and the parameter R, relative advance distance at time of cut off, is useful for determine field operating guidelines.

2 Creating and Managing Projects and Scenarios

WinSRFR projects and scenarios are created, managed and executed using a set of Windows and Dialog Boxes:

Project Management Window

The Project Management Window is the first window to display when WinSRFR is started. This window is used to create, access and manage the various analysis and simulation scenarios that are contained within one WinSRFR project. Each WinSRFR data file (filename.srfr) contains one and only one project, however, a project can contains any number of analysis and simulation scenarios.

WinSRFR World Windows

Each analysis or simulation is associated with a WinSRFR World that provides a distinct set of surface irrigation functions:

Event Analysis World   - Irrigation event analysis and parameter estimation

Physical Design World   - Design optimization of the physical layout of a field

Operations Analysis World   - Operations optimization of irrigations throughout the growing season

Simulation World   - SRFR's irrigation simulation for scenario testing and sensitivity analysis

User Preferences

Individual users can set their personal preferences for colors, fonts, units, etc. using User Preferences found under the Project Management Window's Edit menu. These preferences are stored under the Current User / Software section of the Window's Registry.

Tools

In addition to the windows described above, WinSRFR provides tools to aid in performing irrigation analysis:

Data Comparison Tool   - Parametric and graphical comparison of results from two or more scenarios

Conversion Chart Tool   - Conversion of numeric values between metric and English unit systems

2.1   Project Management Window

The Project Management window displays when WinSRFR starts and is used to create and manage scenarios within a WinSRFR project.
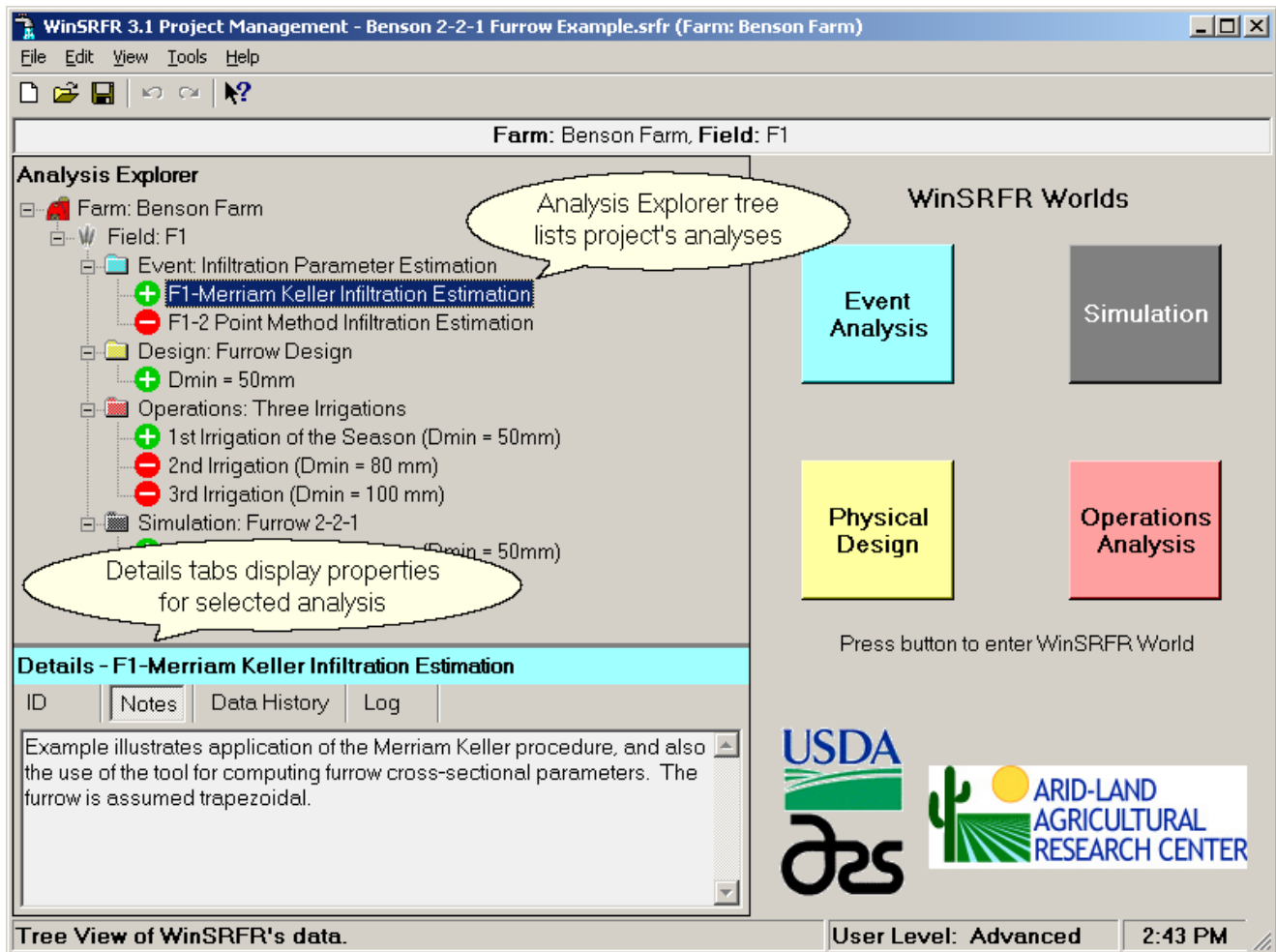
The three main components of the Project Management window are:

- The Analysis Explorer
- The Analysis Details
- The WinSRFR Worlds Buttons

2.1.1   Analysis Explorer

The Analysis Explorer is the main tool for managing your WinSRFR Analyses & Simulations. It displays a hierarchical tree-view of the data within a WinSRFR project. The top three levels are merely containers; they help you organize your Analyses and Simulations that reside at the fourth (i.e. right-most) level. Refer to Data Organization for a discussion of WinSRFR's underlying data.

Containers

The top three levels within the Analysis Explorer are used to organize your data within a WinSRFR project, i.e. a WinSRFR data file (.srfr).

 - The top level container is the Farm; only one Farm per file is allowed.

 - The next level (or branch) of containers are Fields. A Farm contains one or more Fields while a Field contains one or more World Folders.

 - The last level of containers are the World Folders that are associated with the WinSRFR Worlds that run the Analyses or Simulations. Folders group analyses or simulations by functionality. A good strategy, for example, for performing several Event Analyses on the 1st irrigation of a particular field would be to group these analyses together under a single Event Analysis Folder.

Analyses and Simulations
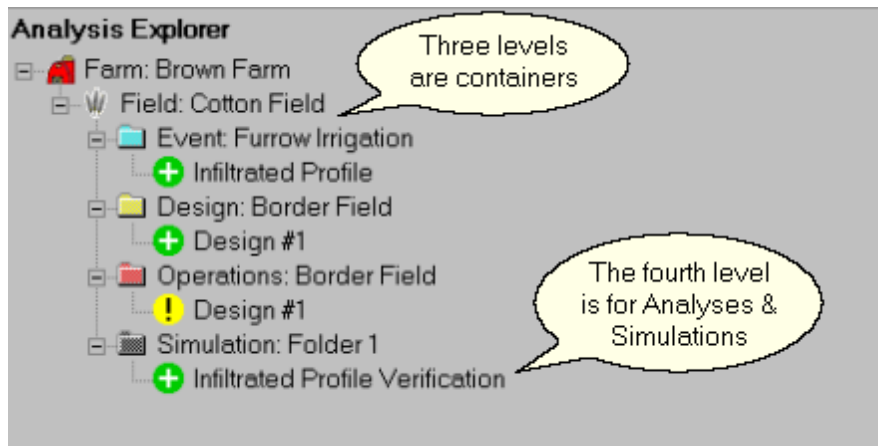
The Analyses and Simulations reside at the fourth level. An Analysis is a complete collection of field data, run criteria and the subsequent run results. To make several runs and save each run's results while varying one or more parameters, create individual Analyses for each run. Use copy / paste to create a duplicate Analysis.

 - The icon associated with an Analysis shows the status of the Run Results. The green plus indicates complete results are available while the yellow exclamation point indicates the run failed to produce valid or a complete set of results. The red minus indicates no results are available.

Context Menus

All items in the Analysis Explorer have associated context menus that can be used to add, copy, and delete folders and scenarios. See Context Menus and Keyboard Navigation for more details.

2.1.2   Analysis Details

The Analysis Details pane is used to identify and document your projects. Two editable and two-non-editable controls are provided for this purpose; Farm, Field and Folder details are limited to ID and Notes.
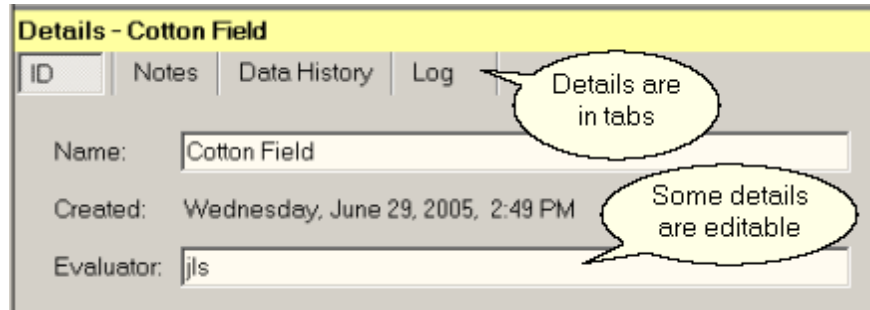
- **ID** - Name of the Farm, Field, World Folder, or Analysis. WinSRFR provides default IDs that you can edit to something more meaningful. Each ID must be unique within its group (e.g., two analyses within a World Folder or World Folders within a Field cannot have the same name).
- **Notes** - Area to document your Farm, Field, and World Folders and Analyses. Documentation data is not required, but is recommended.
- **Data History** - The History of how an Analysis was created. These data are not editable.
- **Log** - A Log of the last five Runs of this Analysis. These data are not editable.

2.1.3   WinSRFR Worlds Buttons

Access to WinSRFR's Worlds is provided by the Project Management Window's Analysis Explorer or by one of the four colored-coded buttons. Pressing a button performs one of the following actions:

1) If no Analysis exists for that World, it will create one.
2) If only one Analysis for that World exists, it will be displayed.
3) Otherwise, you will be directed to use the Analysis Explorer to choose.
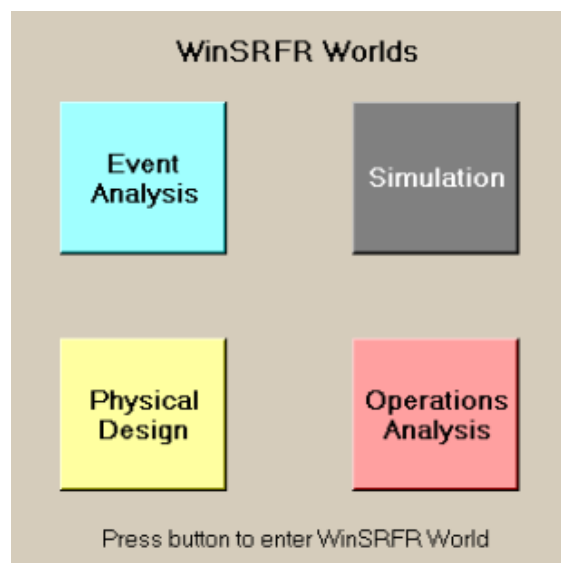
2.2   WinSRFR World Windows

WinSRFR World Windows provide access to the four major functions provided by WinSRFR. There is a common layout to all WinSRFR World Windows including these important features:

Analysis / Simulation Identification

Each Analysis or Simulation is uniquely identified by its Farm, Field, Folder and Analysis names. These names are displayed at the top of every World Window to make it clear which analysis is currently being viewed.
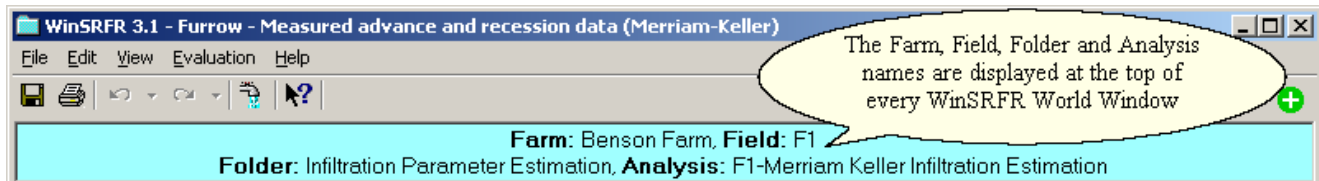
Data Entry Tabs

The World Tab is the left-most tab for any World window (Event Analysis , Physical Design, Operations Analysis, Simulation). From this tab, the user can select the system type (basin, border, or furrow) and the upstream and downstream boundary conditions. Upstream boundary conditions (No Drainback/Drainback) can only be specified for the Simulation World; for other Worlds, No Drainback is assumed. World tabs also provide access to a World's upper level analytical options. For Event Analysis and Simulation, the advance user can also specify field erosion.
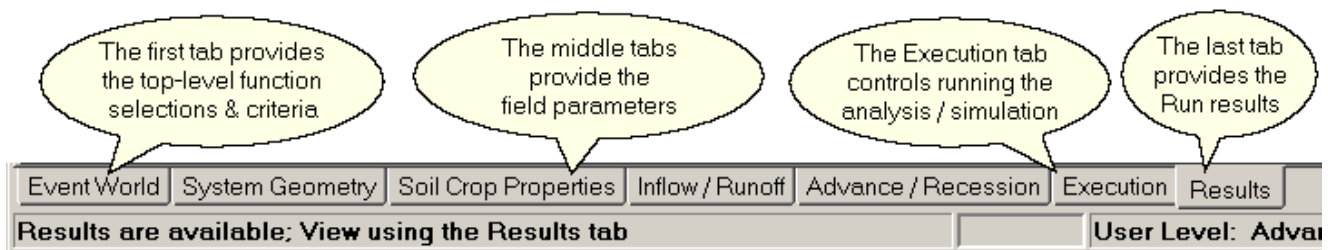
The middle tabs provide access to logically grouped input data including System Geometry, Soil/Crop Properties, Inflow Management as well as world specific input data. The Execution tab provides additional input required to actually generating results within the selected world. The Results tab, the right-most tab, provides access to the Analysis or Simulation results after it has been run.

Results Tabs

After selecting the Results tab as described in the Data Entry Tabs above, the various run results are displayed using a series of tabs displayed at the top of the World Window just below the identification box.
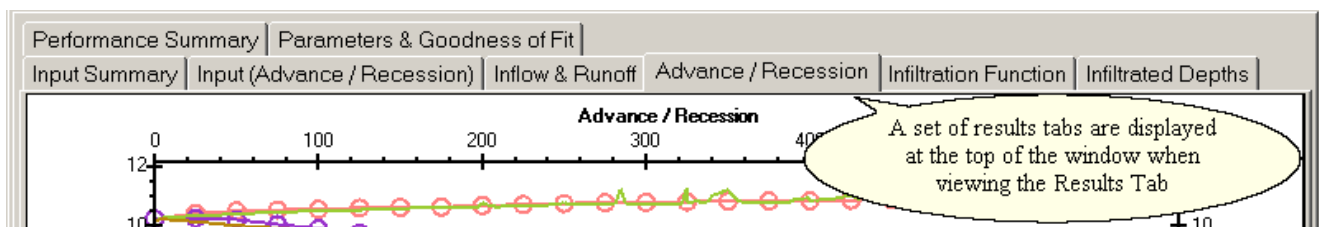
2.2.1   Event Analysis World

The Event Analysis World analyzes the performance of an irrigation using measurements taken before, during and after the irrigation. It can also provide estimates of infiltration and erosion parameters.

For details see: Overview of WinSRFR's Functionality - Event Analysis
                   Working with Scenarios - Irrigation Event Evaluation
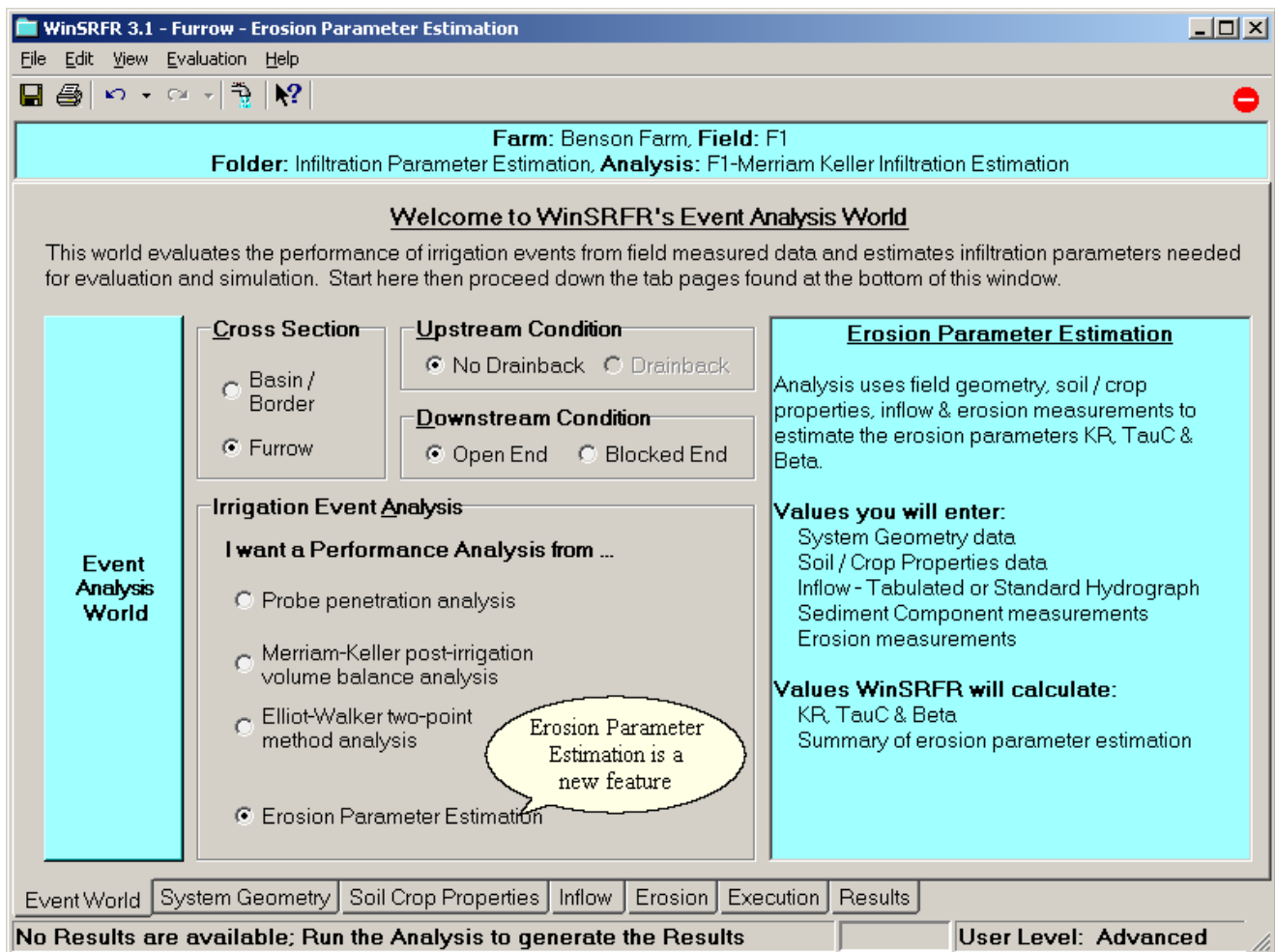
Probe penetration analysis – Evaluate irrigation performance from infiltration profile measurements

Merriam-Keller post-irrigation volume balance analysis – Evaluate infiltration properties and system performance from advance and recession measurements

Elliot-Walker two-point method analysis – Evaluate infiltration properties and system performance from advance measurements at two field locations.

Erosion parameter estimation – THIS FEATURE HAS BEEN DISABLED FOR VERSION 3.1. Evaluate soil erodibility and critical shear parameters from a sediment concentration measurement (new feature)

2.2.2 Physical Design World

The Physical Design World optimizes the **physical layout** of Basin, Border and Furrow fields, specifically, the Length and Width of a field. Other irrigation parameters, such as Inflow Rate, Cutoff Time and Cutback Time, may also be calculated.

For details see: Overview of WinSRFR's Functionality - Physical Design
Working with Scenarios - Sloping Furrow Design
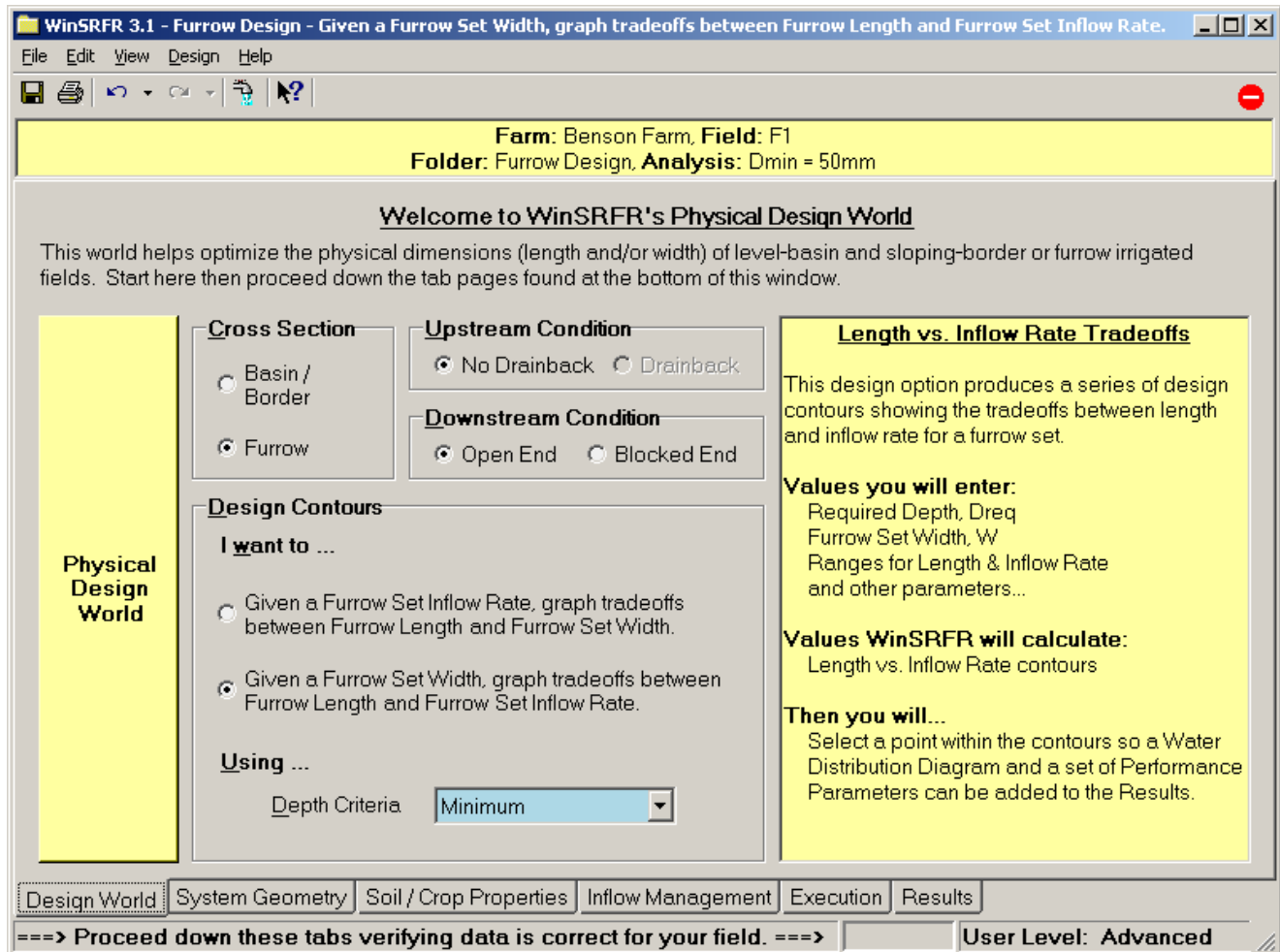
Design Options - two options are available for generating the design contours:
- Length vs. Width contours - Inflow Rate is provided by the user
- Length vs. Inflow Rate - Width is provided by the user

The design can only use minimum depth. For furrows, design can include cutback flow.

2.2.3   Operations Analysis World

The Operations Analysis World optimizes the **irrigation operations** for your Basin, Border and Furrow fields. Irrigation parameters calculated in this world include Inflow Rate, Cutoff Time and Cutback Time.

For details see: Overview of WinSRFR's Functionality - Operational Analysis
　　　　　　　　Working with Scenarios - Border Operations
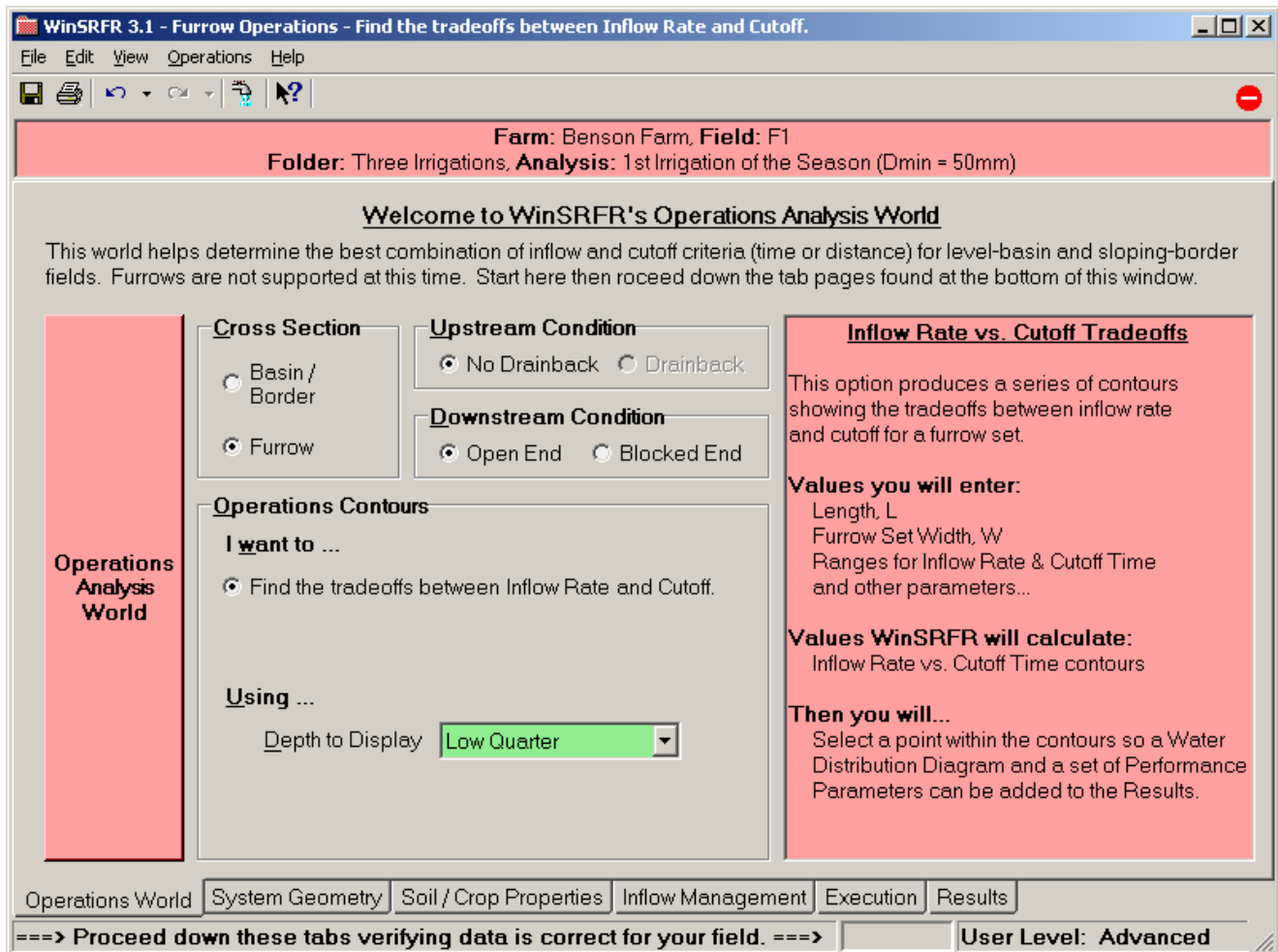
Operations Options - only one option is available for generating the operations contours:
  * Inflow Rate vs. Cutoff contours - Length and Width are provided by the user

Operations can use either the minimum or the low quarter depth. For furrows, operations can include cutback flow.

2.2.4 Simulation World

After a field's **physical layout** is designed using the Physical Design World or the **operations** parameters are set using the Operations Analysis World, the irrigation can be **simulated** using WinSRFR's Simulation Word.

For details see: Overview of WinSRFR's Functionality - Simulation
Working with Scenarios - Hydraulic Simulation and Erosion Simulation

EROSION FEATURE HAS BEEN DISABLED FOR VERSION 3.1.
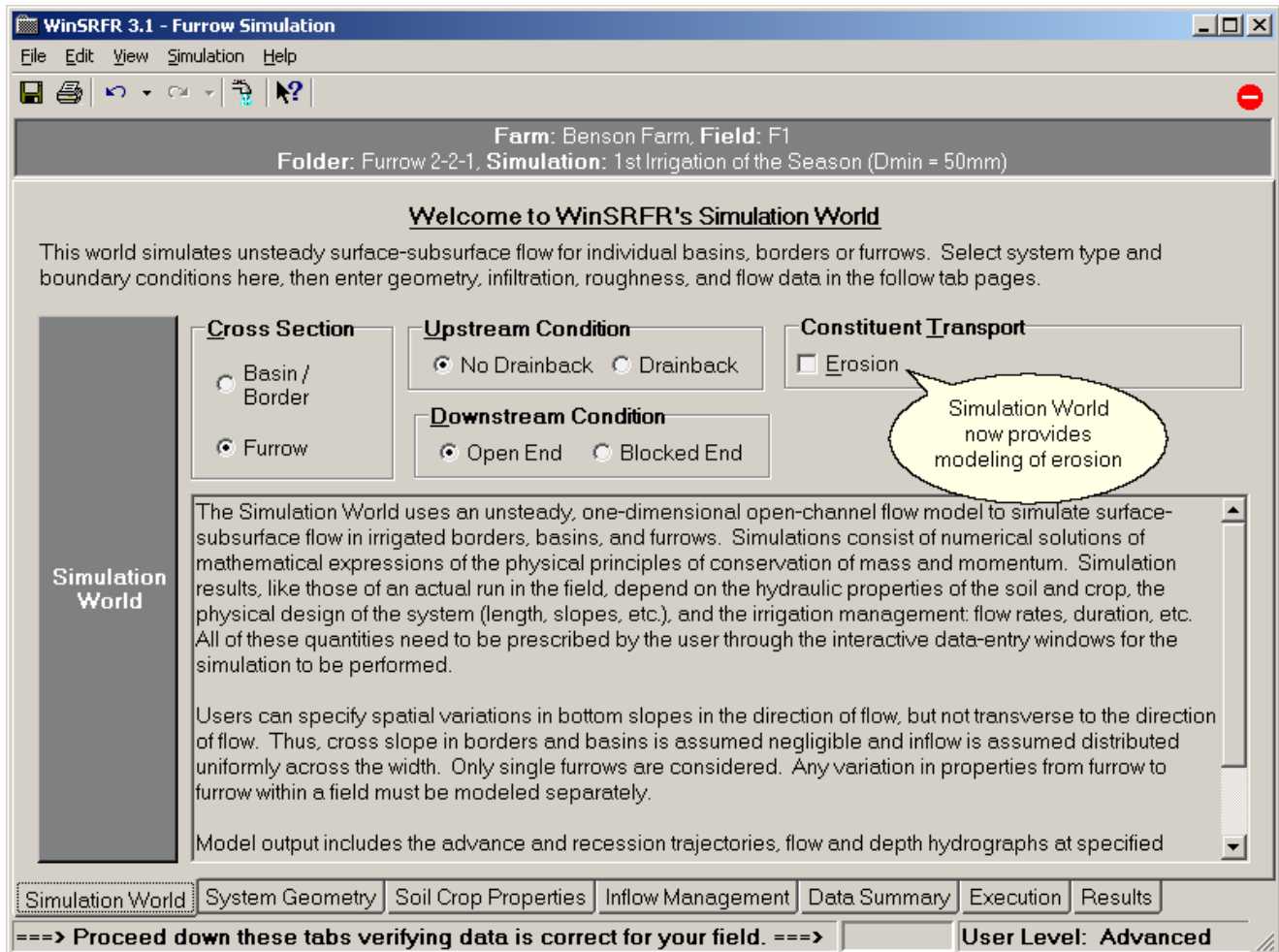
The checkbox, Erosion (available at the Advanced User Level only), enables calculation and display of soil detachment, transport, and deposition in response to the simulated water flow and soil properties.

Simulation of basins, borders and furrows is based on SRFR, a program previously developed by the USWCL.

Water Flow Animation

During the Simulation of an Irrigation, WinSRFR produces an animation of the irrigation water flowing over the field and into the soil. The automatic use of this animation view can be enabled and disabled using User Preferences. It is always available under the Simulation Worlds' View menu.
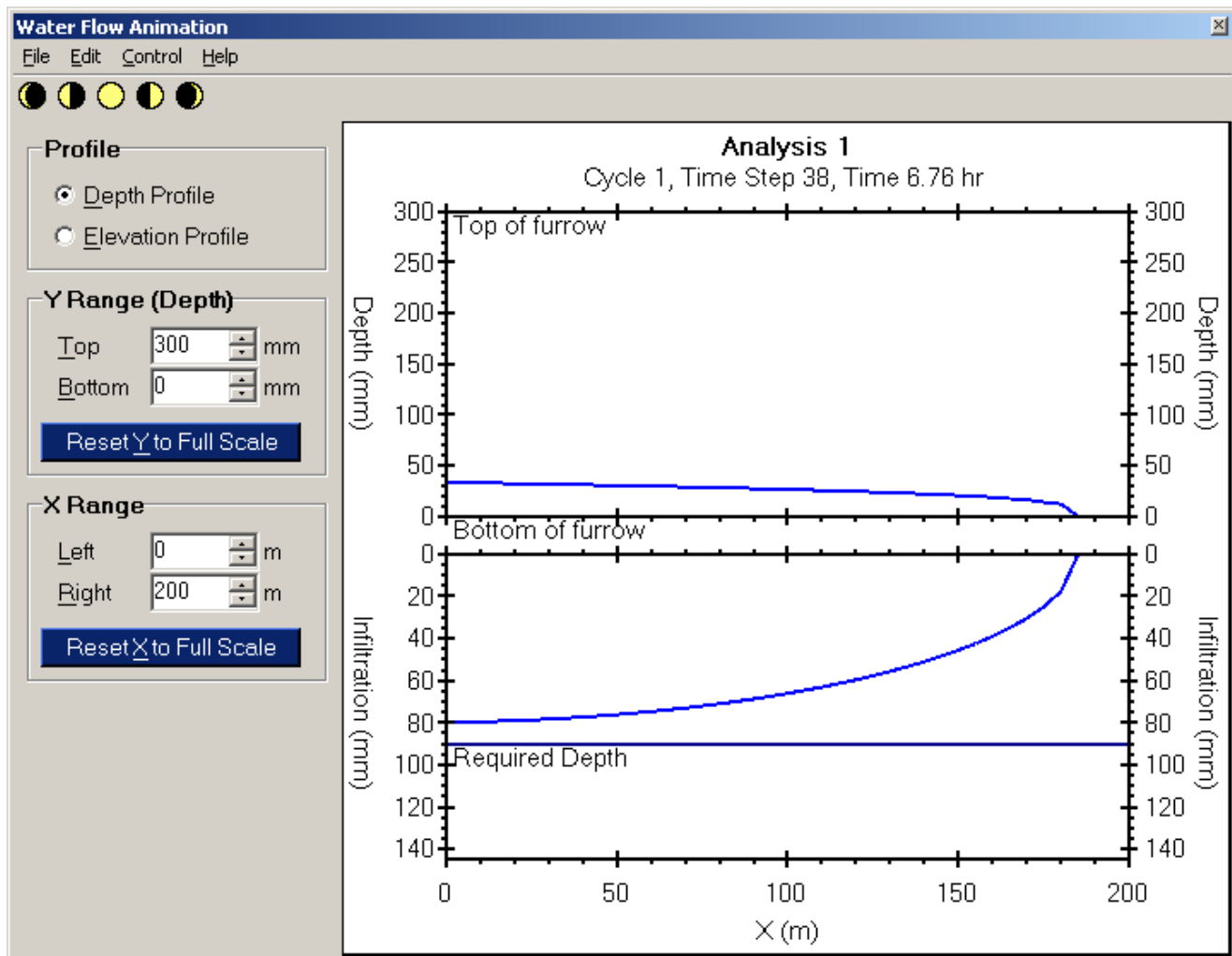
The animation can be controlled much like a VCR. Use the Goto Start, Step Back, Play / Pause, Step Forward and Goto End buttons and menu items to move through the animation frames. At any time, the data in a frame can be copied to the clipboard as a bitmap for pasting into a Word document or as tab separated values for pasting into Excel.

Individual frames can be copied as a bitmap or exported as .bmp, .gif, .jpeg, or .tiff files. The entire animation can be saved as an animated .gif. The data from an individual frame or from the entire animation can be copied to the clipboard for pasting into an application like Excel. Use the Edit menu or the right-click context menu to access these copy and export functions.

2.3   Data Organization and File Management

WinSRFR's data is organized in memory and in a file using a hierarchical structure similar to your PC's file system. The top level of this hierarchy is a Farm (Project). This Farm is similar to a folder in that it holds one or more Fields. Fields, in turn, hold one or more World Folders. A WinSRFR file (filename.srfr) contains the complete set of data for one and only one Farm. The nomenclature Farm / field or Project / Case is user selectable in the User Preferences dialog box.
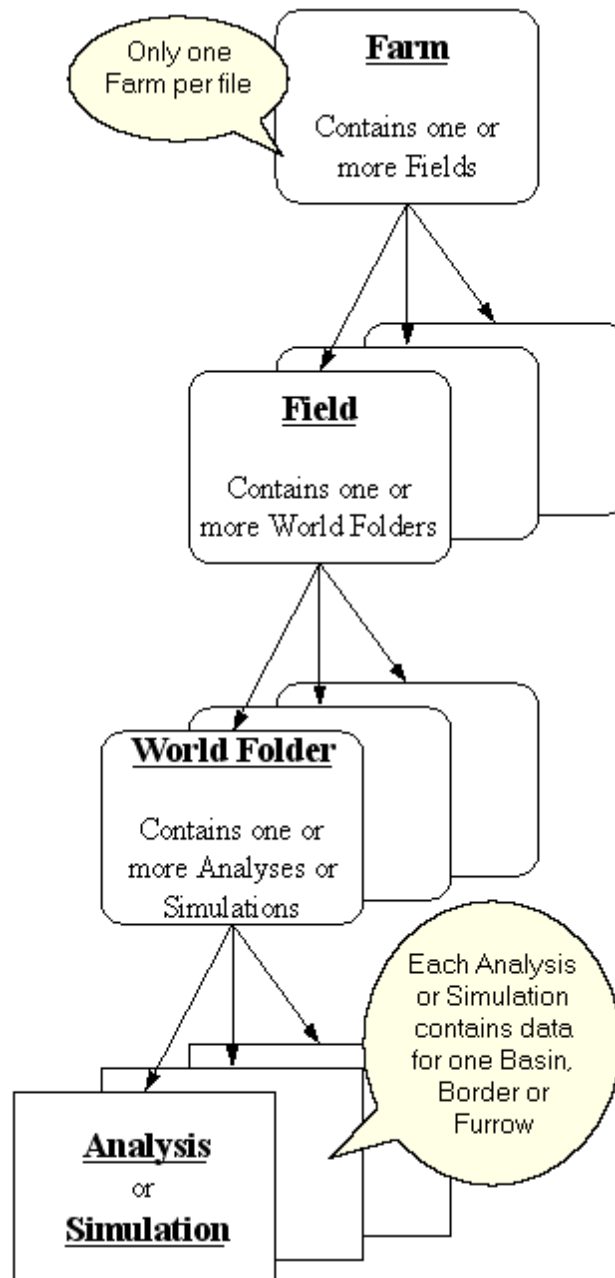
World Folders store the Analyses and Simulations which contain the actual data that WinSRFR operates on. World Folders limit the type of data they store to one WinSRFR World. For example, an Event Folder holds one or more Event Analyses. It cannot hold Design Analyses, Operations Analyses or Simulations. The same is true for all four World Folder types:

World Folder type	Holds
Event Folder	Event Analyses
Design Folder	Design Analyses
Operations Folder	Operations Analyses
Simulation Folder	Simulations

See the Project Management Window and the Analysis Explorer for user interface information related to creating and using these data elements.

2.3.1   Farm, Field & World Folders

WinSRFR uses a hierarchical storage mechanism to manage data in memory and store it in a file.

WinSRFR File (filename.srfr)

A file contains one Farm (Project). When working with more than one farm, each farm's data must be stored in its own file.

Farm (Project)

A Farm contains one or more Fields enabling you to group your data by field since each field may have a different geometry, infiltration characteristics, roughness, etc.

Field (Case)

A Field is a collection of World Folders, representing the different types of WinSRFR analyses applied to that field. As the name implies, a Field enables you to group your data by field (or group fields with similar geometrical, infiltration, and roughness properties). For example, you may have one Event Folder named "1st Irrigation" and a second Event Folder for the same Field named "2nd Irrigation". The same Field can contain a Design Folder named "Basin Designs" and another for "Border Designs". Any type of analysis can be applied to a Field and any field folder can have as many World Folders as needed.

World Folder

A World Folder is a collection of related Analyses or Simulations that contain the actual data that WinSRFR operates on. World Folders limit the type of data they store to their specific world type.. For example, an Event Folder holds one or more Event Analyses, but it cannot hold Physical Design, Operations Analyses, or Simulations, even though the basic data are alike.

You may want to run several analyses on a data set varying only one or a few parameters. If you want to save the results of each run, you should create a new Analysis or Simulation for each run. Analyses and Simulations can be duplicated using Copy & Paste. Using the Analysis Explorer, simply right-click on the Analysis or Simulation and select Cut or Copy to send it to the clipboard. Then right-click on the World Folder you want to Paste it into.

2.3.2 Analyses & Simulations

Analysis and Simulations, the fundamental data objects that WinSRFR works with, contain:

Field Data

> System Geometry data - the physical description of the field's layout
> Soil / Crop Properties data - the field's infiltration and surface roughness characteristics
> Inflow Management data - the description of the flow of irrigation water onto and out of the field

> The type of irrigation system (furrow or border/basin) and the upstream and downstream boundary conditions are included in the **World** (left-most) tab.

Execution

> Functions and options used to run the Analysis or Simulation are usually available in the **Execution** tab.

Results

> The results produced by running the Analysis or Simulation are usually found in the **Results** tab.

Because input data are defined at the level of Analyses and Simulations, each of these objects contain its own set of inputs. Changing an input to one Analysis / Simulation within a World Folder (for example, length) does not change the value for that input for other Analyses / Simulations. Analyses / Simulations within a World Folder typically represent analytical scenarios for the given field. For example, a sensitivity analysis for infiltration can be developed within a Simulation World Folder by defining several scenarios, all with the same inputs except the infiltration properties. Copies of the original Analyses / Simulations can be created using Copy & Paste, as explained later.

Double-clicking an Analysis or Simulation in the Analysis Explorer will display its data in the appropriate WinSRFR World. The field data and run criteria are always available for viewing. Run results, however, are only available after you execute a Run.

Results are available for viewing unless changes are made to the field data or run options; such changes make the output data inconsistent with the inputs. To view the new results, the analysis / simulation must be run again. If both the new and old results need to be saved, the new scenario must be run from a copy of the old scenario. Changes to the input data can be undone by using Edit/Undo. This will restore the original inputs and results.

2.3.3 File Management and Management of File Size

WinSRFR uses conventional file management commands (New, Open, Close, Save, Save As). When using the Open command, WinSRFR automatically resets the default directory data file path to the location of the mostly recently opened file (this does not happen if opening a file from the Recent Projects File list). While operating on a file, WinSRFR generates a diagnostic file that, by default, is located in a subdirectory of the installation folder. The user can use the User Preferences to change the location of this diagnostic file.

NOTE: *Because WinSRFR files store all pertinent input data and extensive tables of results, those files can grow to several megabytes in size. The user can choose to save only the inputs, and rerun the analysis only when needed to review the output data. Use the File/Clear All Results command to delete all results data.*

3   Working with the Graphical User Interface

WinSRFR uses visual elements and Windows services to assist the user in his/her interaction with the program and the data:

Windows and Dialog Boxes help the user navigate through the program's main analytical functions and to function-specific options
Color is used to distinguish the different worlds and to provide data status.
Context Menus provide alternate access to functions for selected items.
Cut, Copy & Paste are used to create new Analyses & Simulations from existing ones.
Help is available online and in PDF form. Both formats present the same content.

WinSRFR uses two main window types, the Project Management Window and World Windows. The Project Management Window provides access to a project's folders/objects. A World Window provides access to a particular Analysis/Simulation and its data. Currently, WinSRFR allows only a single World Window to be open for each World. Dialog Boxes are called by either the Project Management or a World Window, and allow the user to specify user interface and analytical options.

3.1 Visual Elements

Beyond the usual Windows elements, WinSRFR provides an overall look and feel to its User Interface to help you understand the current state of your Analysis or Simulation.

Color is used to distinguish the different worlds and to provide data status.

Context Menus provide alternate access to functions for selected items.

Help is available online and in PDF form. Both formats present the same content.

Data Table Entry describes how to manually enter or paste data into data tables.

3.1.1 Color

Color is used by WinSRFR to provide both context and meaning to the data being displayed. Color provides context by distinguishing which World you are working in and gives additional meaning to data indicating its source or state.

Color of WinSRFR's Worlds

The Worlds supported by WinSRFR are distinguished by each having its own color.

Event Analysis World: Blue
Physical Design World: Yellow
Operations Analysis World: Red
Simulation World: Gray
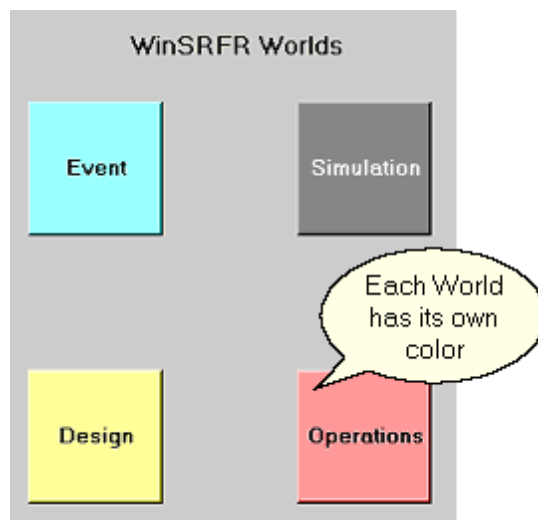
Color of Data

WinSRFR data can be:

Defaulted: Standard window color
User Entered: Green
WinSRFR Calculated: Blue
In Error: Red

Data fields are highlighted with different colors depending on the source or state of the data value.
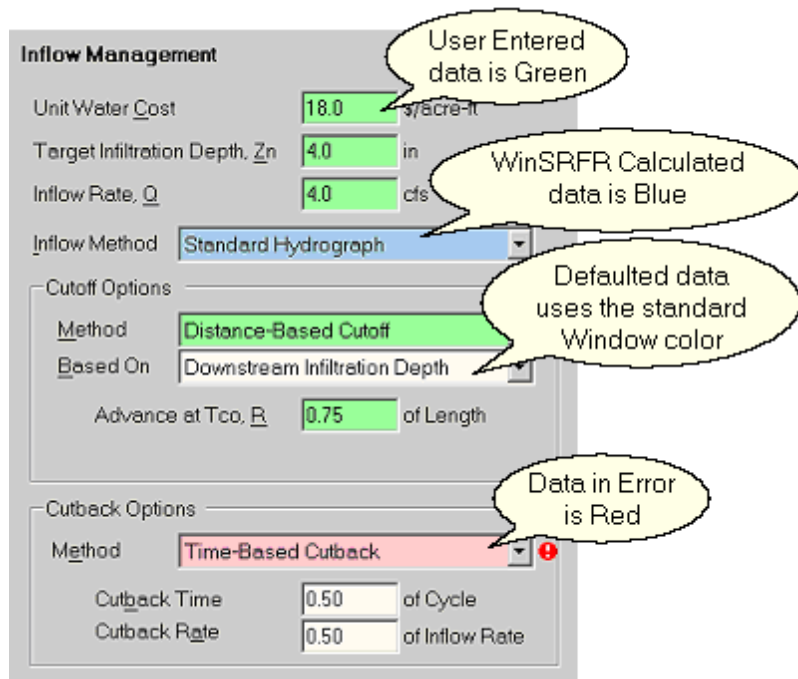
User Entered Data, whether selection or numeric, is displayed in green.

WinSRFR Calculated or Limited Data is displayed in blue. This includes numeric values that have been calculated or are to be calculated by WinSRFR and selection fields that WinSRFR has limited to only one choice.

All data within WinSRFR begins with **Default Data** values that are displayed using the standard Window color. You should always verify that the default data values are correct for your work.

Selections or Data Values In Error are displayed in red with an adjacent red icon. Hover the mouse over the icon to display a tooltip describing the error.

3.1.2 Context Menus

Context menus, specific to the item selected, are used extensively by WinSRFR.

1) By the tree view in the Analysis Explorer.
2) By various graphs in the World Data Tabs and Result Tabs.
3) For Data Table entry.

Analysis Explorer Context Menus

Context Menus in the Analysis Explorer are accessed by either clicking the right-mouse button on an item or by pressing the space bar after selecting an item using the arrow keys. Clicking the left-mouse button outside the Context Menu or pressing the escape (Esc) key removes the menu.
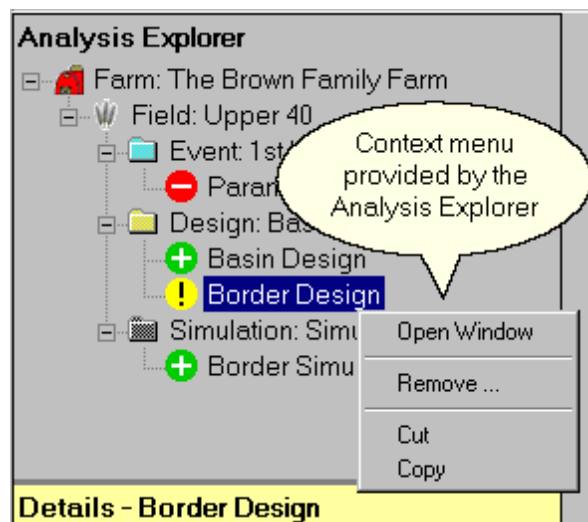
Graphic Context Menus

Context Menus provided by graphs can only be accessed by clicking the right-mouse on the graph; the main menu provides access to the functions provided in the Context Menus.
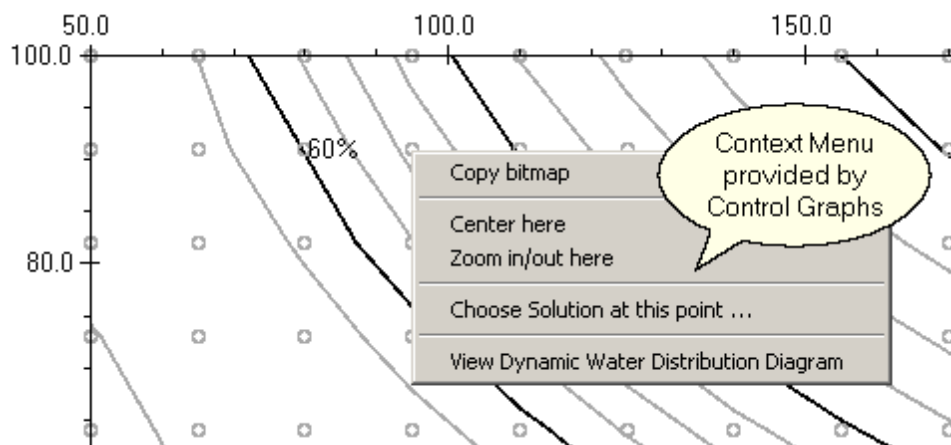
3.1.3 Help

WinSRFR provides help through many mechanisms, most of which are standard in Windows applications:

F1 Key

Pressing the F1 key at any time will display the section in the online help most appropriate to the window that has focus.

What's This? Help

What's This? help is accessed under the Help menu or via its toolbar button. Once selected the question mark mouse pointer is displayed until a control is clicked. At that time a short description of the control is displayed. This display is removed by clicking the mouse again.

Tooltips

Tooltips are displayed by hovering the mouse over a control. Tooltips are only used where they add value.

Help Menus

Each window provides a Help menu for access to commonly requested help items.

Help Buttons

Most dialog boxes have a Help button in the lower right corner. Pressing this button provides help for that dialog box.

PDF Manual

The help provided online by WinSRFR is also available in PDF format. Both the online help and the PDF manual are produced from the same source so they provide the same content.

3.1.4   Data Table Entry

Data Tables are used throughout WinSRFR for entry and display of tabular data. They appear in Window's forms, as shown below, as well as in Dialog Boxes. Data can be entered manually, pasted from the clipboard or imported from a file. Once entered, data can be copied to the clipboard and exported to a file. It is important to remember that when data is imported or pasted into a Data Table, the new data must have compatible columns of data both in number and data type.

Menu items for all Data Tables are found in the File and Edit menus as well as in Context Menus. The File Menu is used for Importing and Exporting tabular data. There is File menu entry for every Data Table being displayed. The Data Table's name is displayed as the menu item's name.

The file to the left contains data ready to be imported into a Profilometer Data table. Note that the first line in this file contains the units applicable to each column of data. If this line is present, the units specified will be used when the file is imported. If this line is missing, the units currently being displayed by WinSRFR will be used. Of course, a Profilometer Data file exported by WinSRFR can always be imported later. Files are checked to ensure they have a valid number of rows and columns and the right type of data in each column. Error message(s) will be displayed if the data is not valid or incompatible with the current setup.

Similarly, the Edit Menu is used for inserting & deleting rows as well as for other editing functions such as Clear, Copy and Paste.
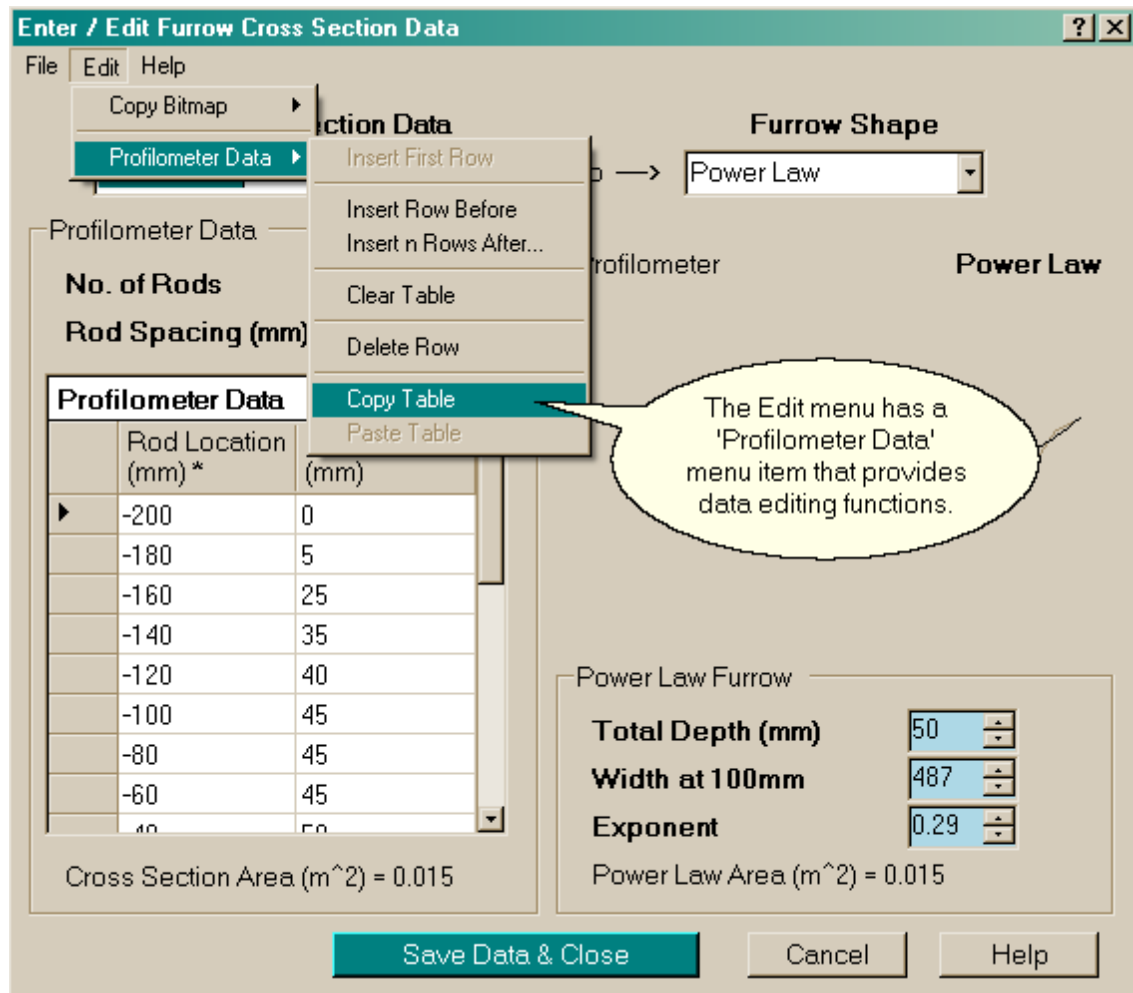
Besides being in the File and Edit menus, these functions are also available in <u>Context Menus</u> directly in the Data Table. Right-click with the mouse on the table or row to display the corresponding Context Menu.

When pasting data from an application like Excel, the first row may contain the units to apply to each column. If the units are copied to the clipboard, they will be used when pasting the data into WinSRFR. If the units are not copied, the row data will use the units currently being displayed by WinSRFR.

3.2   Dialog Boxes

Most WinSRFR dialog boxes have a Help button in the lower-right corner to displays a help page describing its use; Help is available for the following dialog boxes:

- Units
- User Preferences
- Match Infiltration Method
- Edit Furrow Cross Section Data
- Slope / Elevation Table Entry
- Choose Solution
- Add Contour Overlay
- Standard Simulation Criteria
- Advanced Simulation Criteria

3.3 Keyboard Navigation

WinSRFR can be operated using the keyboard alone; use of the mouse is not required. Some of the ways a user can navigate the various windows and dialog boxes using only the keyboard are documented below.

Menus

To activate any Menu item:

1) Press and release the "Alt" key. This selects the first menu in the menu bar and underlines the activation keys for all menu items.

2a) Use the arrow keys to traverse the menu to select the item you want then press the "Enter" key.
or
2b) Press the underlined activation key for the desired menu item.

Tab Pages

To select a tab page:

1) Use the "Tab" key to move focus to the tabs.

2) Use the arrow keys to select the tab page.

Numeric Controls

To select a numeric entry control:

1a) Use the "Tab" key to move the focus to the control. "Tab" moves the focus forward while "Shift-Tab" moves focus backward.
or
1b) Use the "Alt" as you would the shift key to select the numeric control. All 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 selected a particular control if it is in a group of controls that share a single label.

To edit the value of a numeric entry control:

2) When a numeric control has focus, its value is usually highlighted. You can simply type in a new value at this point or use the arrow keys to position the cursor to a point where you can edit the current value.

3a) Press "Enter". The new value will be entered and focus will stay on the control.
or
3b) Press "Tab". The new value will be entered and focus will move to the next control.

Selection Controls

To select a selection control:

   1a) Use the "Tab" key to move the focus to the control. "Tab" moves the focus forward while "Shift-Tab" moves focus backward.

or

   1b) Use the "Alt" as you would the shift key to select the control. All 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 selected a particular control if it is in a group of controls share a single label.

To edit the value of a selection control:

   2) Use the arrow keys to move through the selections.

Check Box Controls

To change the state of a check box control:

   1) Use the "Tab" key to move focus to the check box.

   2) Use the "Space bar" to change the state.

Buttons

To press a button:

   1a) Use the "Tab" key to move the focus to the button. "Tab" moves the focus forward while "Shift-Tab" moves focus backward. Use the "Space Bar" to 'press' the button.

or

   1b) Use the "Alt" as you would the shift key to press the button. All 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.

Analysis Explorer

To use the [Project Management window](#)'s [Analysis Explorer](#):

   1) Use the "Tab" key to move the focus to the Analysis Explorer. "Tab" moves the focus forward while "Shift-Tab" moves focus backward.

   2) Use the arrow keys to move around in the explorer. The up and down arrows move through the visible items. The left moves up through the items closing levels as it goes. The right arrow moves down through the items opening levels as it goes.

3a) Once you have selected an Analysis or Simulation, press the "Enter" key to display it in its corresponding WinSRFR World.

or

3b) 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.

Function / Control Keys

Some functions can be accessed directly by using function or control keys:

F1	- Help
F5	- Refresh display

Ctrl-X	- Cut
Ctrl-C	- Copy
Ctrl-V	- Paste

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

All Windows

Ctrl-S	- Save
Ctrl-Y	- Redo
Ctrl-Z	- Undo

3.4 Error & Warning Messages

WinSRFR makes extensive use of error and warning messages to help and guide the user.

Data Entry Errors

Individual data entry fields or tables may validate the data entered by the user for obvious errors and immediately report the errors for correction.
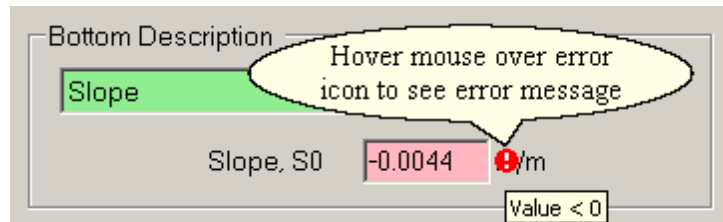
Other errors or warnings may not become apparent until a set of data has been entered that, taken together, are inconsistent.

Most errors and warnings fall into two categories:

- Setup Errors & Warnings - errors or warnings associated with the user's input data
- Execution Errors & Warnings - errors or warnings generated when running an analysis or simulation

3.4.1   Setup Errors & Warnings

Setup Errors & Warnings are detected prior to running the analysis; these errors and warning apply to the data input by the user.

Setup Errors - occur when data has been entered that is not yet defined, invalid or incomplete. These error prevent the analysis from being executed since the analysis requires complete, valid data to yield useable results. Setup errors must be corrected prior to running the analysis.
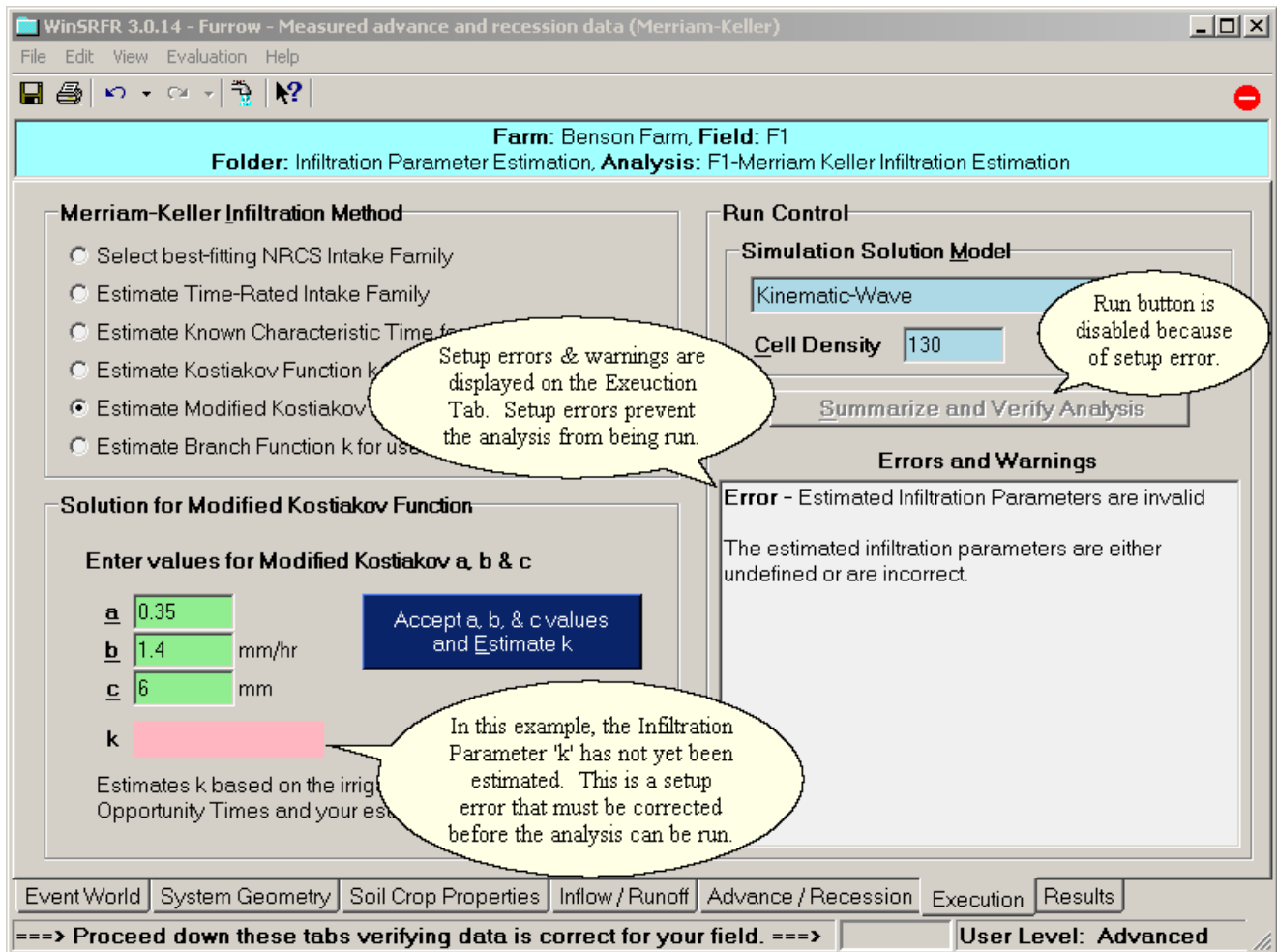
Setup Warnings - occur when data has been entered that WinSRFR determines to possibly being problematic. This data could yield invalid results but WinSRFR has no way of verifying this so the user is warned to validate suspect data prior to running the analysis.

Warnings may appear in one or more locations as shown in the example below.

3.4.2   Execution Errors & Warnings

Execution errors & warnings are generated while an analysis or simulation is running.

Execution Errors - usually occur during a simulation run where input conditions result in a model that cannot be correctly simulated. WinSRFR tries to avoid these conditions but is not always able to do so. In these circumstances, the error is communicated to the user to deal with. Sometimes, making a small adjustment to an input condition will alleviate the error.
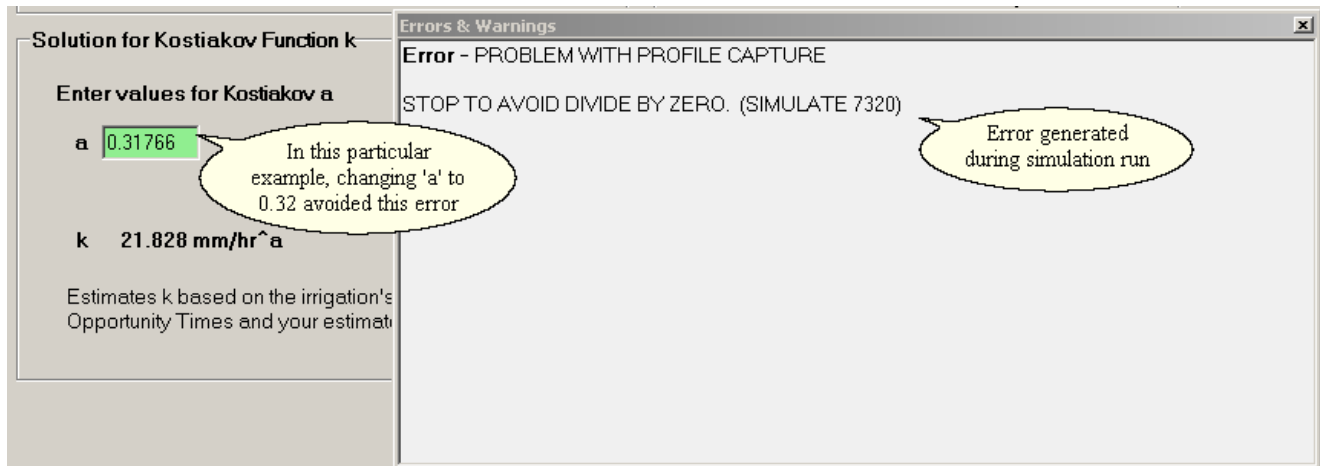
Execution Warnings - may originate as Setup Warnings but are carried through to the Results so the user does not lose track of them. Other execution warnings are generated as a result of the run; an example from an analysis run that is producing operations contours is shown below:
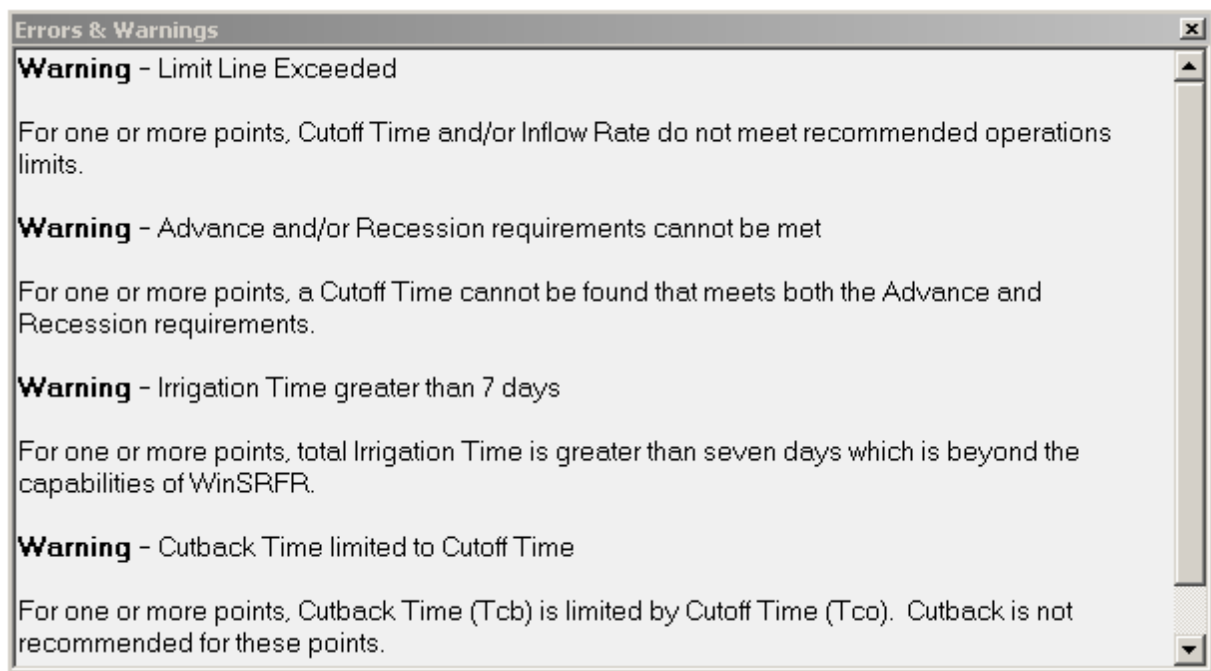
3.5   Setting the User Level

The User Level determines whether users can make changes to or access advanced program execution options and features. For most analyses, users do not need to change these execution options from their default values and, furthermore, changes should only be made by users knowledgeable of the program's computational procedures.

Use the Edit / User Level menu item on the main <u>Project Management Window</u> to change the User Level.

Three User Levels are provided by WinSRFR:

Standard

The Standard User Level provides functionality that should be sufficient to most WinSRFR users. This option disables the access to the advanced program execution options. Erosion procedures are not available at the Standard User Level.

Advanced

The Advanced User Level enables access to the advanced program execution options. These include:

- In the Simulation and Event Analysis Worlds, erosion simulation and estimation of erosion parameters
- In the Simulation World, calculation of hydraulic resistance with the Manning Cn/An and the Sayre-Albertson formulations.
- In the Simulation and Event Analysis Worlds, manual selection of the solution engine (zero-inertia or kinematic-wave)
- In the Simulation World, execution tab, Advanced Criteria

Programmer

The Programmer User Level is reserved for ALARC personnel to aid in testing and debugging WinSRFR. It allows access to options that can disable a simulation in ways difficult to debug

3.6   Setting the User Preferences

User Preferences allow user-customized aspects and defaults for WinSRFR's User Interface and function execution. These preferences vary from user to user on the same PC as they are stored in the Current User section of the Window's Registry. User Preferences are grouped depending on their use and application:

Startup - Default values for application-wide data
Views   - Options for enabling / disabling and controlling WinSRFR views
Files   - Paths to commonly used files / folders
Dialogs - Options controlling whether or not certain dialog boxes are displayed
Units   - Units system and default units selection
Graphs - Colors and options to use for graphs
Contours - Colors and options to use for contours

3.6.1   Startup

The Startup tab sets default values in new projects including the Farm Name, Owner, and Default Evaluator; these three fields can be left blank. The user can select whether or not the last file opened is automatically re-opened when WinSRFR is started.

Farm Name   - default name used when a new Farm / Project is created
Farm Owner   - default name used for the Farm's Owner
Evaluator   - default name of person running WinSRFR; used when a new Analysis / Simulation is created

Check box   - selects whether or not the previously opened file should be re-opened at startup
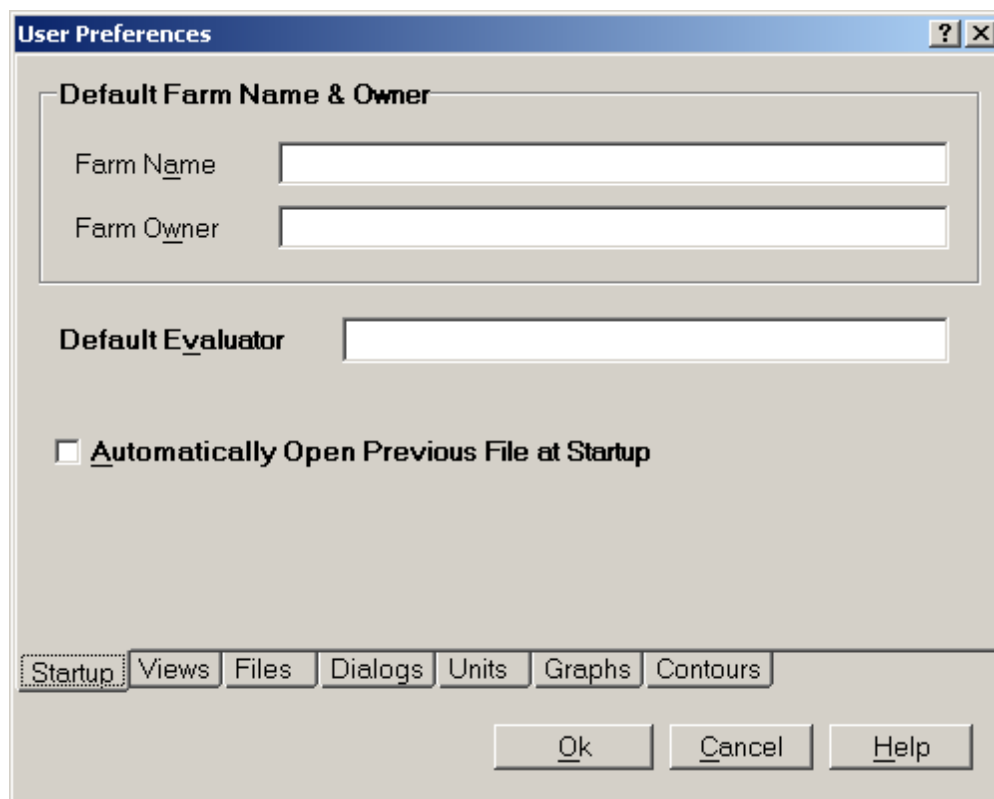
3.6.2   Views

The Views tab determines whether graphical outputs will be displayed on screen as charts only or in print preview mode, with additional text included. It is also used to control the display of the simulation animation window.

Default Results View
       Portrait Page   - all Results are displayed on a Portrait page (Print Preview-like view)
       Graphs Only   - graphs fill the available window; text results display on a Portrait page

Check box   - selects whether or not the Simulation Animation will automatically display when a
Simulation is run
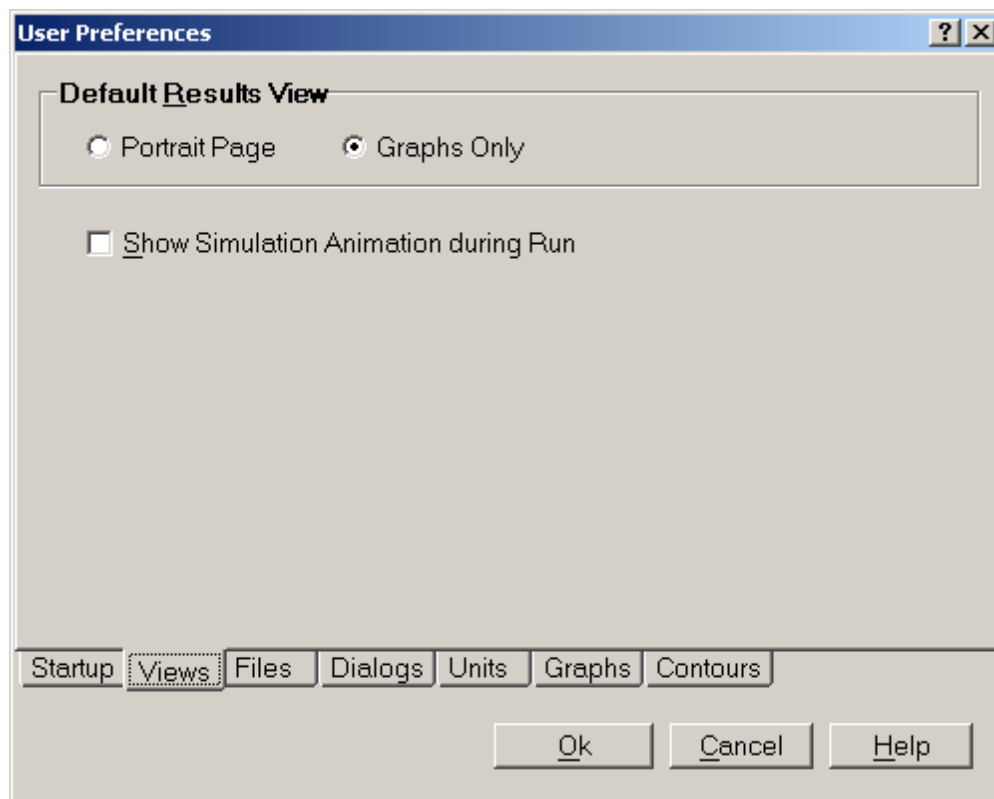
3.6.3 Files

The Files tab sets the path for the WinSRFR diagnostic files.

Log & Diagnostic File Folder - path to the folder for WinSRFR's log and diagnostics files.

By default, the pathname is set to the folder provided by Windows for application data:

C:\Documents and Settings\...\Application Data\USDA\WinSRFR 3.1

The user can change to any path that can be more easily accessed than the default value.
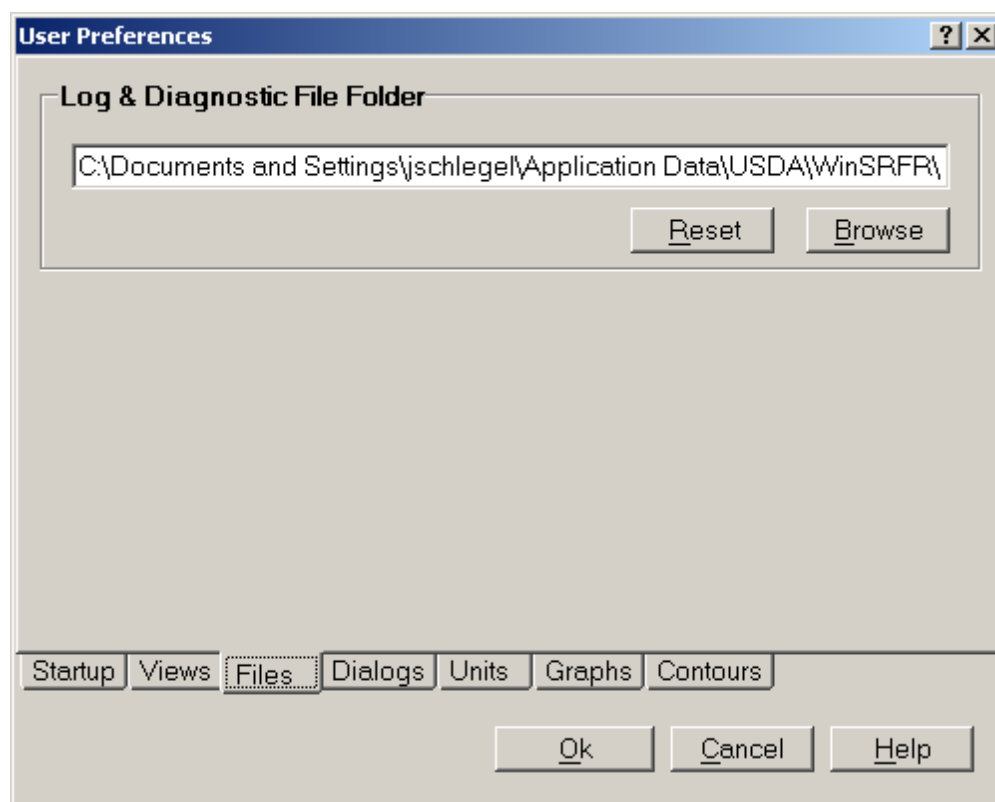
3.6.4 Dialogs

The Dialogs tab controls the display of two dialogs:

Suggested Default Values - controls whether or not to confirm suggested changes to the Solution Model or Cell Density when running a Simulation

- Unconditionally Accept   - automatically use recommended values without confirmation
- Require Confirmation   - verify recommended values with a dialog box to confirm changes

The Infiltration Function options control how infiltration parameters will be processed when changing the infiltration formula in the World Window/Soil and Crops Properties tab. The assumption is that in some cases the user will want to keep the existing values but in others will want to keep the shape of the function, independent of the parameter values. The No Matching option simply keeps the existing parameter values. Both the Auto Matching and Confirmed Matching fit the parameters to match the shape of the previously defined infiltration function. Auto Matching does this automatically, while Confirmed Matching displays a dialog box with a chart of the currently defined function and the alternative function, and controls that can be used to manipulate the shape of the alternative function.

Infiltration Function - controls what happens when a new Infiltration Function is selected.

- No Matching   - keeps infiltration parameters independent from selection to selection
- Auto Matching   - automatically matches parameters for new Infiltration Function with old function
- Confirmed Matching   - displays dialog box to confirm changes
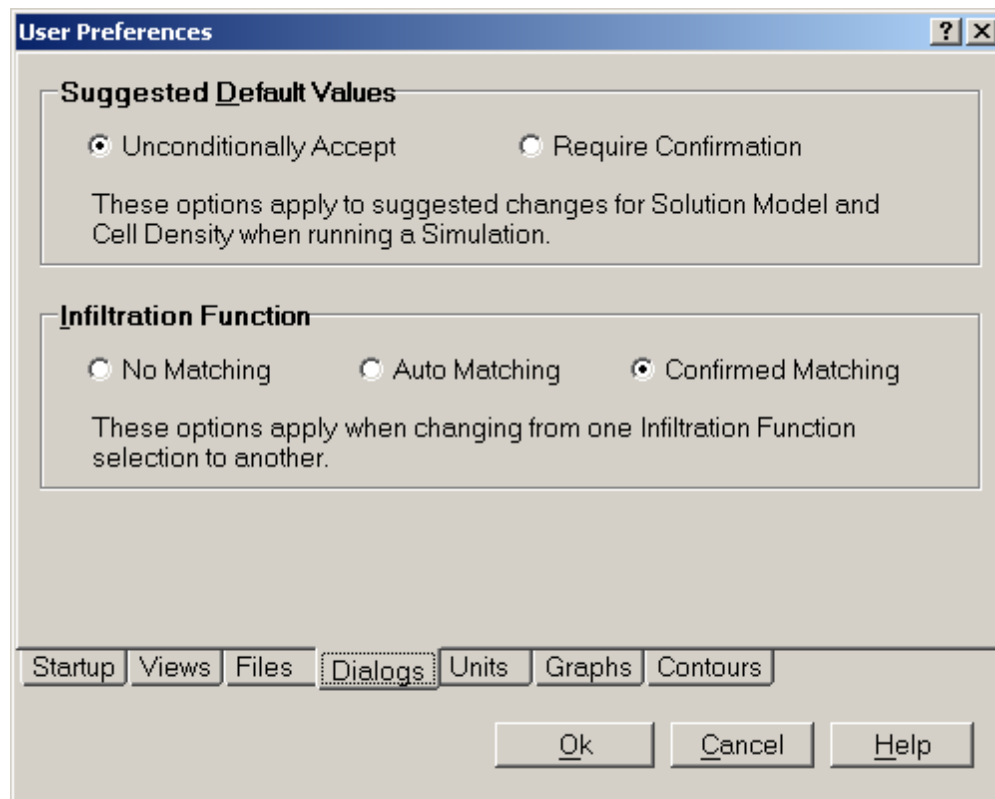
3.6.5 Units

The Units tab determines whether English or metric units are used by default in both input and output forms. The specific default units for a given variable have been selected based on units typically used in practice. For example, if working in English units, field lengths are typically measured in ft and depths are measured in inches.

NOTE : For a session, the user can choose the units of individual input boxes (for example, change from gpm to lps). Unit labels appear to the right of variable input boxes. Units are changed by right-clicking on the label and selecting an alternative unit measure from the resulting drop-down list.

Default Unit System   - selects whether Metric or English units are used as the default units system
         Options   - allows selection of individual units for specific data types

Default Time Units   - selects whether Hours or Minutes are used as the default time units
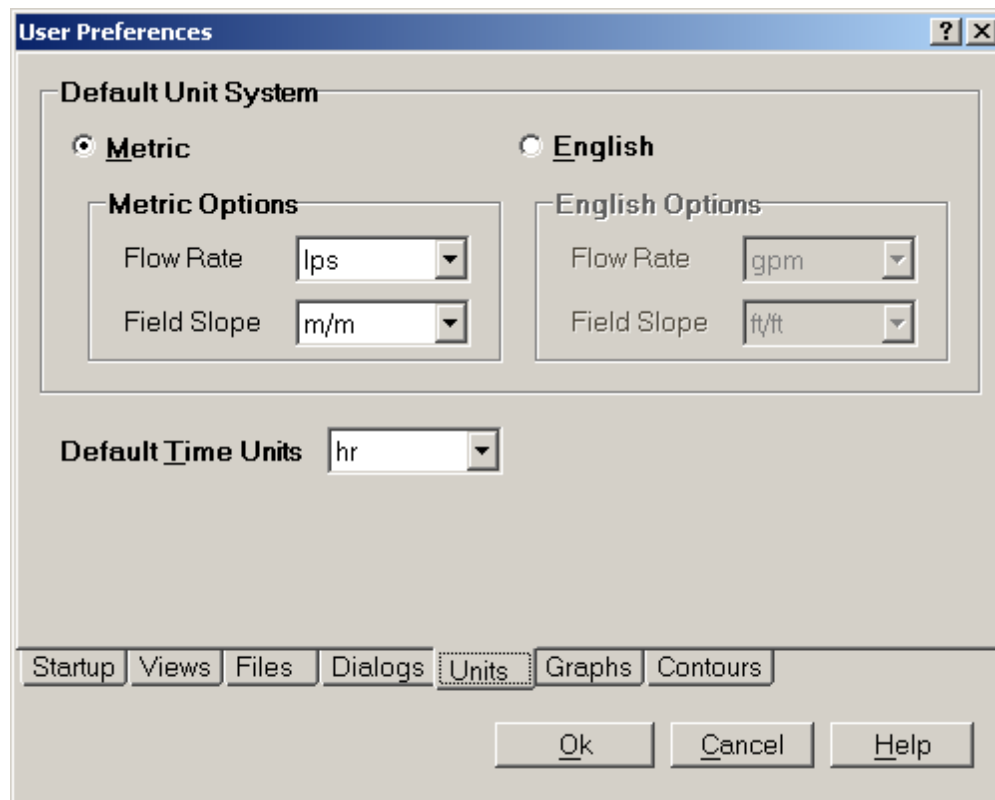
3.6.6 Graphs

The Graphs tab controls the sequence of colors used to plot series of lines on a graph. It also controls the display of a graph's text.

Line Colors   - selects the colors and order for individual lines when drawing graph lines.

Graph Options   - selects whether or not to display graph text.

Font   - selects the graph's font and font size scaling adjustment factor.
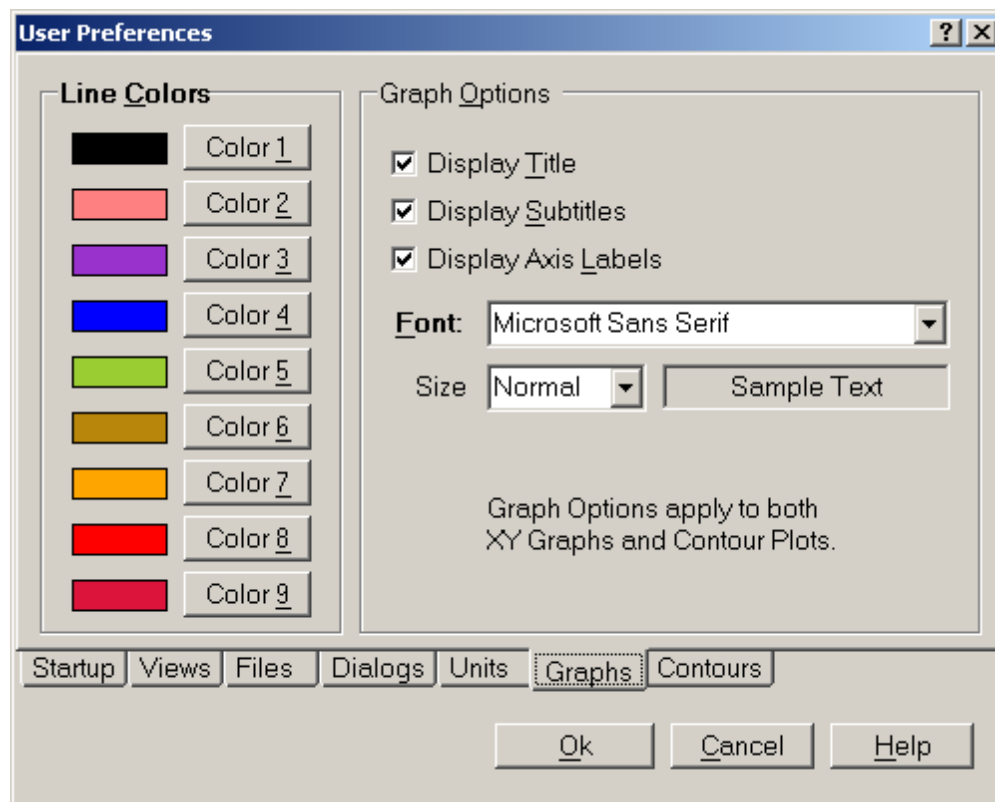
3.6.7   Contours

The Contours tab controls the colors used to fill the design and operations contours as well as other contour options.

Contour Fill Colors   - selects the colors to use to fill the contour levels

Contour Options   - selects whether or not to display various contour elements
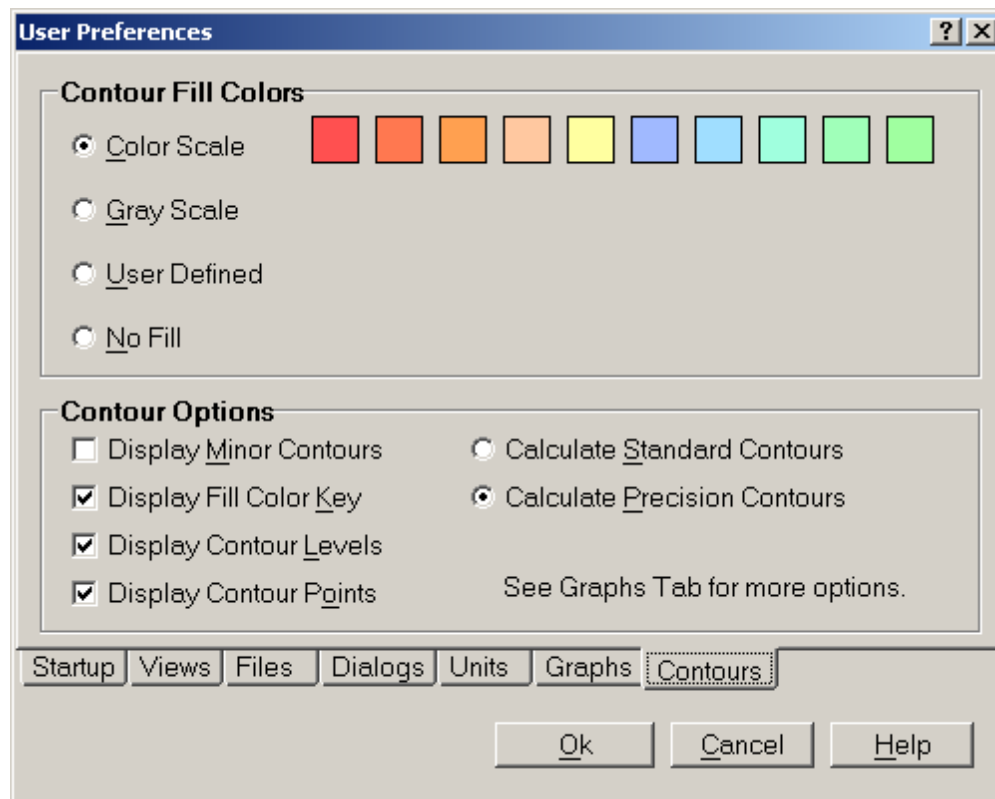
3.7 Setting the Units

Data stored in memory and in the .srfr file are in SI units, however, WinSRFR allows selection of Metric or English units for the user interface. Additional options for each choice allow further tailoring of units to the users needs. Three mechanisms for changing the user interface's units are provided:

1. Setting default units for all projects - use the User Preferences' Units tab
2. Setting default units for the active project - use the Edit / Units menu item
3. Setting units for individual inputs - use context menu for individual input

Setting default units for the active project

The Edit / Menu dialog box allows users the choose either Metric or English units and specific unit options.
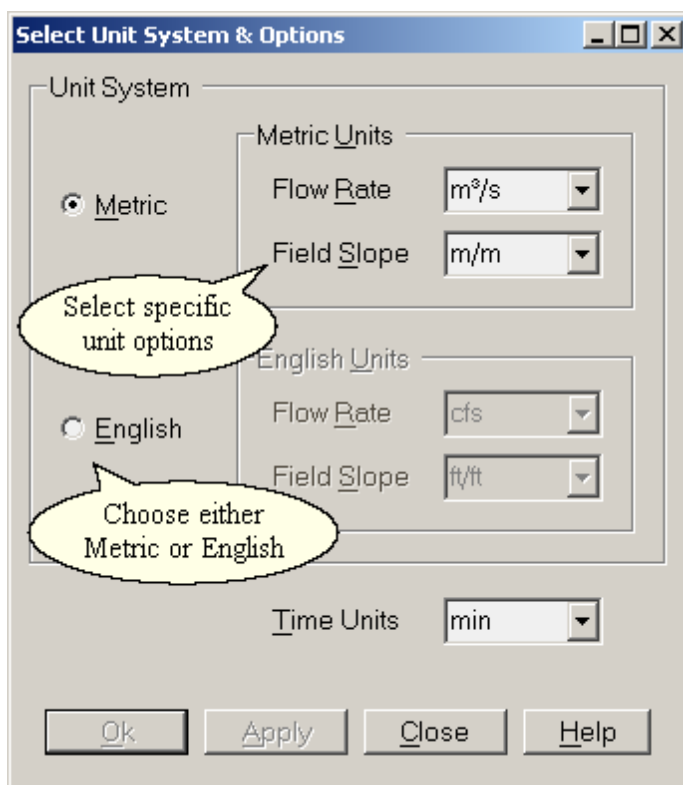
Setting units individual inputs

Numeric input controls that display units provide context menus to select the units for that individual input control. Simply right-click the mouse on the units to display the context menu.
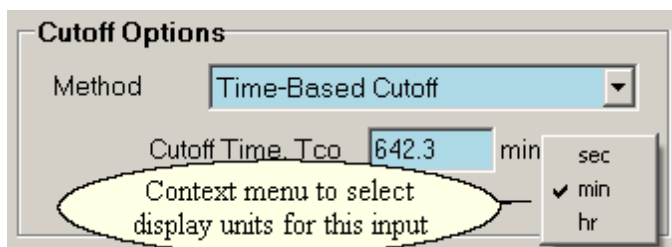
3.8 Setting the Nomenclature Defaults

The user has the choice of what nomenclature is used when referring to the top two levels data organization:

1. **Farm / Field** - useful when working with irrigations in the field
2. **Project / Case** - useful when conducting irrigation research in the lab or office
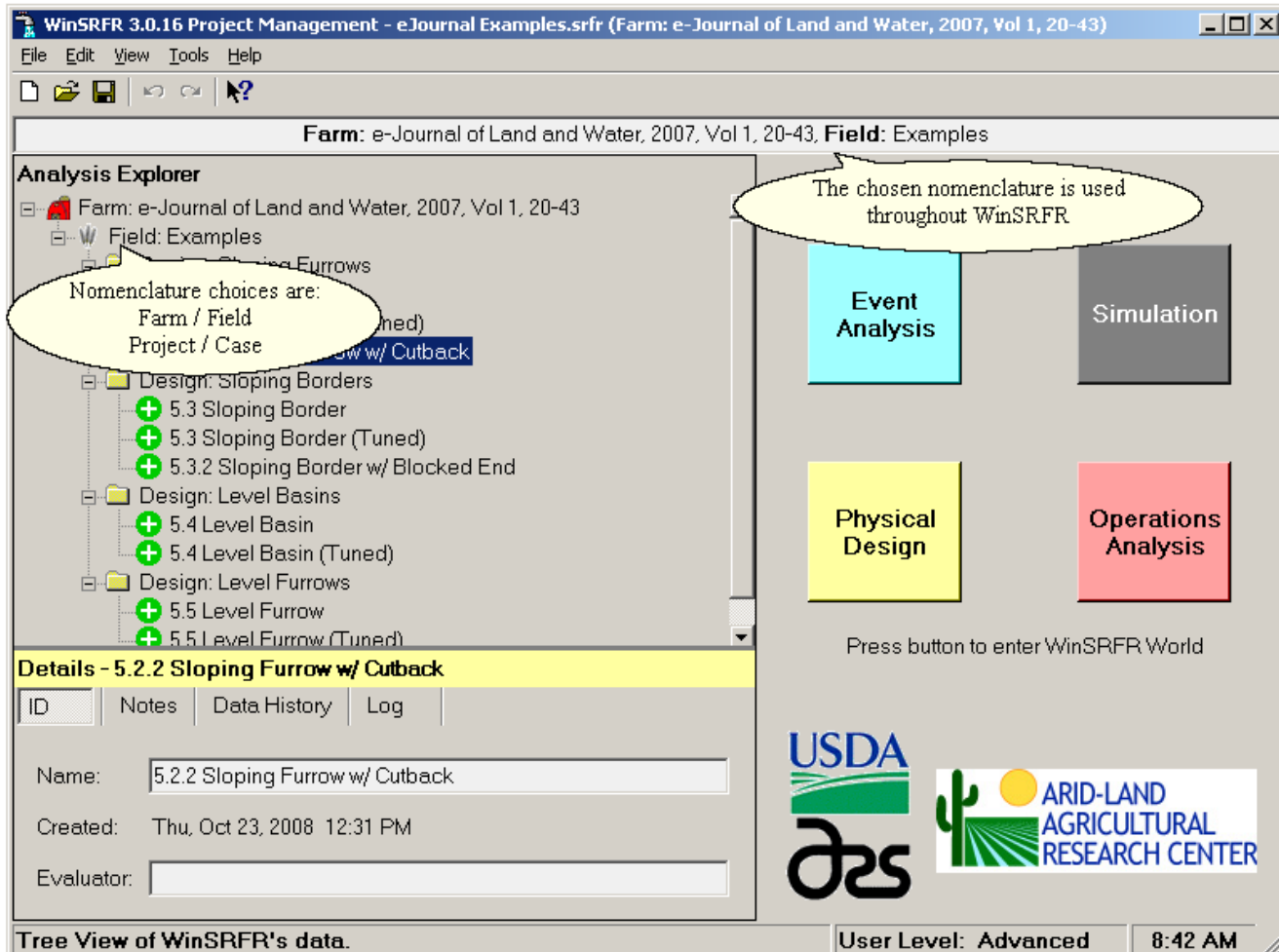
Selecting which nomenclature to use is accomplished using the Edit / Nomenclature menu item.
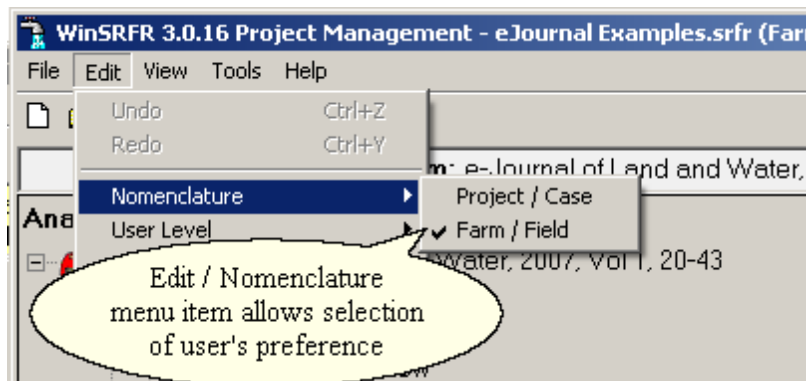
3.9   Data Exchange

WinSRFR supports data movement and 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 spreadsheet to WinSRFR, or from WinSRFR to spreadsheets/word processing software. You can also copy WinSRFR graphical outputs to Windows applications that accept bitmaps, gifs, tiffs, etc. When copying tabular data to WinSRFR, the number of columns in the source data needs to match the number of columns in the receiver form (for example, if copying field elevation data, the receiver form expects two columns of data, consisting of longitudinal distance and vertical elevation pairs). When copying spreadsheet data to WinSRFR, you can label the first row in the data with unit labels. If WinSRFR recognizes the unit labels, it will make the necessary unit conversions. WinSRFR recognizes the following unit labels:

Variable	Unit Labels
Length	"m", "ft"
Depth	"mm", "cm", "in"
Side Slope	"H/V"
Slope	"m/m", "m/100m", "ft/ft", "ft/100ft"
Time	"sec", "min", "hr", _
Flow Rate	"cms", "lps", "lpm", "cfs", "gpm"
Percentage	"%"
Soil Water Holding Capacity	"mm/m", "in/ft"

Import / Export WinSRFR data to / from files

All tables in WinSRFR support importing data from a file and exporting data to a file; see import/export for more details.

3.9.1   Cut / Copy / Paste

The Analysis Explorer uses Cut, Copy & Paste to:

   1) Move item from one location to another (Cut & Paste)
   2) Make a new copy of item (Copy & Paste)

For example, if you want to run a Simulation on the Border Design in the list shown below, perform these steps:

   a) Copy the Border Design to the clipboard using its Context Menu.
   b) Select a Simulation World Folder.
   c) Paste the Border Design into the Simulation World Folder using its Context Menu.

To **Cut or Copy**, right-click on an Analysis or Simulation then select Cut or Copy in the context menu. Pressing the space bar also displays the context menu for the selected item in the Analysis Explorer. Use the arrow keys to choose the menu item then press Enter to invoke it. Cut & Copy are also available for World Folders and Fields.
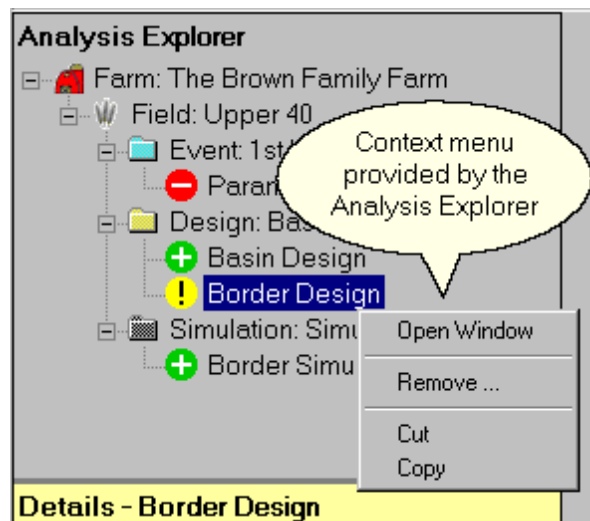
To **Paste**, right-click on a World Folder then select Paste Analysis or Simulation in the context menu. Paste is also available for pasting World Folders into Fields & Fields into Farms.

If possible, the new item keeps the same name; you may modify the name using the Analysis Details view shown below the Analysis Explorer. If an item with the same name is already in the folder, the pasted item's name will be modified by appending a sequence number.

3.9.2   Import / Export

All tables in WinSRFR support importing data from a file and exporting data to a file. The example below is from the Inflow / Runoff tab in the Event Analysis World when performing a Merriam-Keller analysis of an irrigation. Required information for the Merriam-Keller analysis include the inflow to the field and runoff from the field. For this example both were measured and input as tabulated data.

This tabulated data could have been entered into a text file then imported into WinSRFR or entered directly into WinSRFR then exported to a text file if desired.

Exporting the Furrow Runoff Rate table, as shown above, results in the text file shown to the left.

<-- Note - column headings that contain both the column's name as well as the column's units.

This file can be imported back into the Furrow Runoff Rate table at any time.

When importing data, WinSRFR looks for headings that contain column units to correctly interrupt the values that follow. If no units are found, WinSRFR defaults to the table's current display units.

Obviously, without the column heading units, this data could be misinterpreted by WinSRFR when being imported.

3.10 Tools

Additional Tools provided by WinSRFR are found under the Tools menu on the <u>Project Management Window</u>.:

- <u>Data Comparison Tool</u>
- <u>Conversion Chart Tool</u>

3.10.1 Data Comparison

The Data Comparison Tool combines and compares parametric and graphical results from Analyses and Simulations. Use the check boxes in the **Data Explorer** to select the analyses to include and the option buttons in the **Type of Data to Compare** box to select the type of outputs to generate (e.g., advance/recession). Use the tabs at the top of the chart window to select the particular chart to view. To change the sequence of colors used to display the different series, use the User Preferences / Color command (you will need to exit the Data Comparison Tool and return to the Project Management Window). You can send the output to a color printer and copy and paste the displayed information to other Windows applications, either as bitmaps or as tabular data.

To clear selections, uncheck the corresponding boxes in the Data Explorer. You can also click on the menu command Edit/Clear all Selections to simultaneously unselect all analyses.
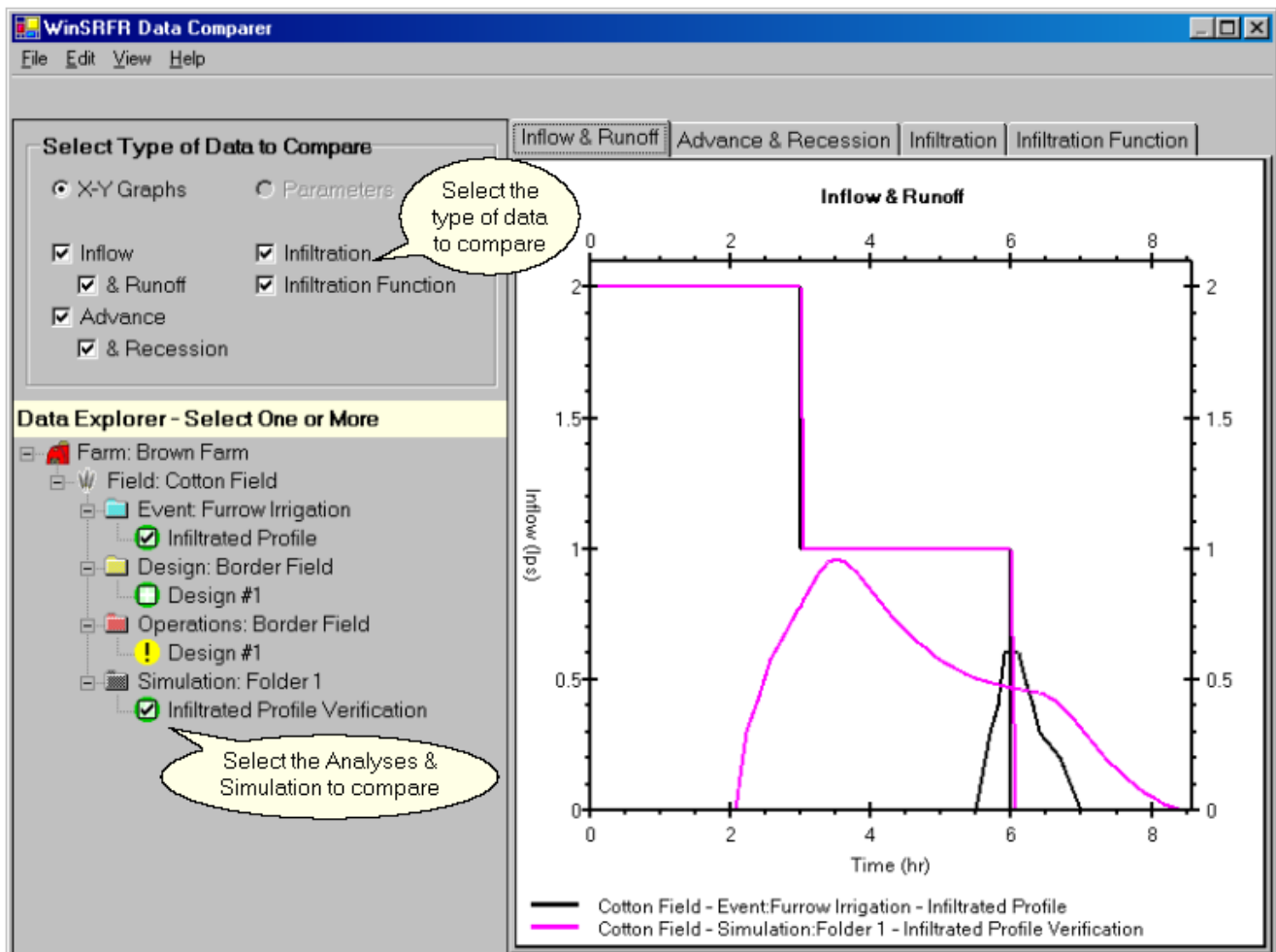
3.10.2 Unit Conversion Chart

From the Project Management Window, click on the Tools / Conversion Chart command to access WinSRFR's Unit Conversion tool. You can use the tool for converting lengths, areas, volumes, and discharges from one unit system to another. Each tabbed form displays a variable in five common unit systems. Enter the known value in the corresponding box and then press Enter.

The Conversion Chart Tool lets you convert English values to Metric and vice versa. It also provides a conversion chart for data types commonly used in WinSRFR:

- Length
- Area
- Depth
- Volume
- Flow Rate

To convert a value from English to Metric, select the appropriate tab then enter the value and press Enter. The equivalent value will be displayed in the other fields on that tab. Do the same for Metric to English.

4   Working with Scenarios

This section provides example scenarios to illustrate the use of WinSRFR's functionality. Each scenario provides a series of steps to help you understand how to use WinSRFR to improve your surface irrigations. Topics include:

- Defining the Common Irrigation System Properties including:

  - System Geometry - defines the geometrical layout (i.e. Length, Width, Depth, Slope, ...)
  - Soil Crop Properties - describes the field's hydraulic roughness and infiltration characteristics
  - Inflow Management - enter data related to field inflows and outflows

- Irrigation Event Analyses including:

  - Probe Penetration Analysis
  - Merriam-Keller Analysis
  - Elliot-Walker Two-Point Analysis

- Design Analysis including:

  - Furrow Design
  - Basin / Border Design

- Operations Analysis including:

  - Basin / Border / Furrow Operations

- Simulation

  - Hydraulic Simulation
  - Erosion Simulation

4.1   Defining the Irrigation System's Basic Properties: Common Input Tabs

The WinSRFR World Windows provide the interface for editing input data associated with a particular analysis and for viewing the corresponding results. All World Windows are organized similarly using tab controls, with each tabbed page representing a category of input or output data. There are two rows of tabs in a World Window, a lower row for inputs and a upper row for results. The last tab in the lower row displays the Results and activates the upper row of tabs.

Three data entry tabs are common to all Worlds: System Geometry, Soil / Crop Properties and Inflow Management. Although these data entry tabs are common across all Worlds, there are variations in what data is to be input and what options are available from world to world.

- **World** Tab (first tab in all World Windows) - refer to WinSRFR World Windows
  - Event Analysis
  - Physical Design
  - Operations Analysis
  - Simulation

- **Common Input Tabs (3)** (to the right of the World tab) - detailed in this section
  - System Geometry
  - Soil/Crop Properties
  - Inflow Management

- **Analysis** Tab (to the left of the Execution) - specific to analysis type
  - Probe Penetration Analysis
  - Merriam-Keller Post-Irrigation Volume Balance
  - Elliot-Walker Two-Point Analysis
  - Erosion Parameter Estimation
  - Hydraulic Simulation
  - Erosion Simulation

- **Execution** Tab (to the left of the Results tab) - specific to analysis type
  - Probe Penetration Analysis
  - Merriam-Keller Post-Irrigation Volume Balance
  - Elliot-Walker Two-Point Analysis
  - Design Analysis / Operations Analysis
  - Simulation

- **Results** Tab (last tab in all World Windows)
  - Probe Penetration Analysis
  - Merriam-Keller Post-Irrigation Volume Balance
  - Elliot-Walker Two-Point Analysis
  - Design Analysis / Operations Analysis
  - Simulation

4.1.1   System Geometry

The System Geometry tab is used to define the irrigation system's geometrical layout. Because different types of analysis (Event, Design, Operations, Simulation) require different sets of geometrical inputs, the input controls displayed by the Geometry tab vary somewhat by World. In cases where a variable is an output of the analysis (e.g. Length, when designing a system), the input box displays either TBD (to be determined), or the output of the analysis (once the analysis is run). That value then is not user-editable. What physical layout features are available is dependent on the WinSRFR World and **Field Type**. The Field Type, selected using the World Tab, consists of:

- **Cross Section** (Basin, Border, Furrow)
- **Upstream Conditions** (Drainback, No Drainback)
- **Downstream Conditions** (Open End, Closed End)

NOTE: In this tab as well as in other tabs, the expected unit system for a variable is displayed to the right of an input control. Default units are assigned to each variable depending on the unit system selected under User Preferences. For a particular session, you can modify the units of individual variables by right-clicking on the label and selecting an alternative from the displayed unit label list

Inputs provided by the System Geometry tab include:

- **Length** – length of the system along the direction of flow

- **Width/Furrow Spacing** - width of the system perpendicular to the direction of flow; width applies to basins and borders, furrow spacing to furrows. Furrow spacing is used to compute the infiltrated depth (volume/length/width), hence, when modeling a furrow system where every-other-furrow is irrigated, twice the nominal furrow spacing needs to be entered to calculate a representative average application depth.

- **Maximum Depth** – depth at which water will overflow. For borders and basins, it is the height of the berms. For furrows, it is the maximum depth used to compute the furrow's cross section. If the computed water depth at any point exceeds this maximum depth, the SRFR simulation engine will issue an OVERFLOW warning (see the output Summary Tab). In overflowing furrows, the assumption that neighboring furrows behave identically allows the simulation to proceed with lateral furrow boundaries midway between the given and adjacent furrows. These boundaries, while confining the furrow flow, contribute nothing to surface roughness or infiltrations, as do the solid boundaries below. In furrows, the simulation is as realistic as the similarity between adjacent furrows. In borders or basins, the actual lateral loss of water to a neighboring, dry border strip or basin is not modeled when the same assumption as for furrows is applied. The user must reduce the inflow or increase the berm height or furrow depth to prevent an overflow from occurring in the field.

- **Bottom description** – WinSRFR provides five options for describing the field bottom. These are accessible using the Bottom Description drop-down list:

  o **Slope** – average field slope (Total vertical drop / Field Length). An input box will be displayed to enter the slope value. This is the only option displayed when working in the Physical Design or Operational Analysis Worlds, as the built-in procedures assume a constant slope.

  o **Slope Table** – Table of longitudinal distances vs. slope. Each entry in the table is a location where the average slope changes. Therefore, a slope value needs to be given at distance zero; the last entry is assumed to be the average slope in the last portion of the field. The Edit Table button appears when this option is selected. Pressing the button will launch the Slope Table dialog. This dialog box is described in more detail further below.

  o **Elevation Table** – Table of vertical field elevations vs. distance. Each entry in the table represents a surveyed elevation-distance pair. At a minimum, an elevation at the upstream and downstream end of the field needs to be entered and the downstream location needs to match the defined field length. As in the Slope Table, elevation values are edited using the Elevation Table dialog.

  o **Average From Slope Table** – This option computes an average slope from tabulated slope values. Tabular data needs to be entered as in the Slope Table option. After entering a Slope Table, the user can switch at any time between this option and the Slope Table option.

  o **Average From Elevation Table** – This option computes an average slope from tabulated elevations. Tabular data needs to be entered as in the Elevation Table option. After entering an Elevation Table, the user can switch at any time between this option and the Elevation Table option.

- **Furrow Shape and Dimensions** -This option is displayed only when the Furrow option is selected in a World Tab. Furrow cross-sectional area can be described generally using either a trapezoidal or parabolic section, hence options for defining furrow cross section are the following:

  o **Trapezoid** – a trapezoidal section is defined by two parameters, the Bottom Width and the Side Slope (Horizontal/Vertical). Input boxes for those two parameters will be displayed when the Trapezoid option is selected.
  o **Power Law** – a power law or parabolic section is defined by a relationship of the form $TW=C*Y^M$ where TW is the top width, Y is the depth, 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 user will need to enter m and the top width value at 100 mm (4 in). These values will be used to compute C.
  o **Trapezoid from Field Data** – This option allows the user to enter field data and to calculate the corresponding trapezoidal section parameters. An Edit Data button will appear when this option is selected. Pressing this button will launch the Enter/Edit Furrow Cross Section dialog, which is described further below.
  o **Power Law from Field Data** – This option is similar to the previous one, except that it launches the Furrow Cross Section dialog with power law options selected.

4.1.1.1 Edit Furrow Cross Section Data

WinSRFR defines a furrow cross section as either a trapezoid or a power law function which is convenient for mathematical operations but may not be easy to define. The Enter / Edit Furrow Cross Section Data dialog box enables entering furrow cross section data as measured in the field. WinSRFR can 'best fit' these data to either a trapezoid or power law. Three methods are available for defining furrow cross section data:

- Depth / Top Width Table - a series of furrow depth / top width pairs
- Profilometer Table - furrow depths as a function of transverse distance as measured using a Profilometer
- Flow Cross Section - a series of furrow depth / top width pairs, with depths given at the bottom, middle, and top of the furrow depth

These methods are explained with the help of the figures below, which depict typical furrow cross-sectional data and the resulting WinSRFR data entries. In **Figure a**, the red horizontal lines represent top width measurements taken at three arbitrary depths, 0.71, 2.36, and 3.15 in. In the figure, the labels above or next to the red lines are the corresponding top width value. The symbols represent measurements of furrow depth (Y) vs. transverse distance (X) taken on a regular X-Y grid with a profilometer. In many field situations, the evaluator will take a few top width measurements at arbitrary depths. In such cases, the depth/top width option would be selected and the resulting table for the data of **Figure a** would be as given in **Figure b**. If detailed profilometer data are available instead, then the Profilometer option should be selected and the resulting table would be as given in **Figure c**. The Flow Cross Section option is similar to the Depth/Top Width option except that WinSRFR fixes the depths at the bottom, middle, and top of the furrow.

As with the tabular bottom elevation data, cross sectional tabular data can be entered manually, by importing a text file, or by copying/pasting from a spreadsheet. Notice that for this example, from **Figure a**, the vertical origin of the profilometer measurements is at the bottom of the furrow. However, the Dialog box expects data with the origin at the top of the furrow. If data is copy/pasted from a spreadsheet and those data have their origin at the bottom of the furrow, WinSRFR will make the necessary calculations to set the origin at the furrow top. Import and copy/paste operations will replace existing tabular data so export any data that you need to save prior to making any changes.
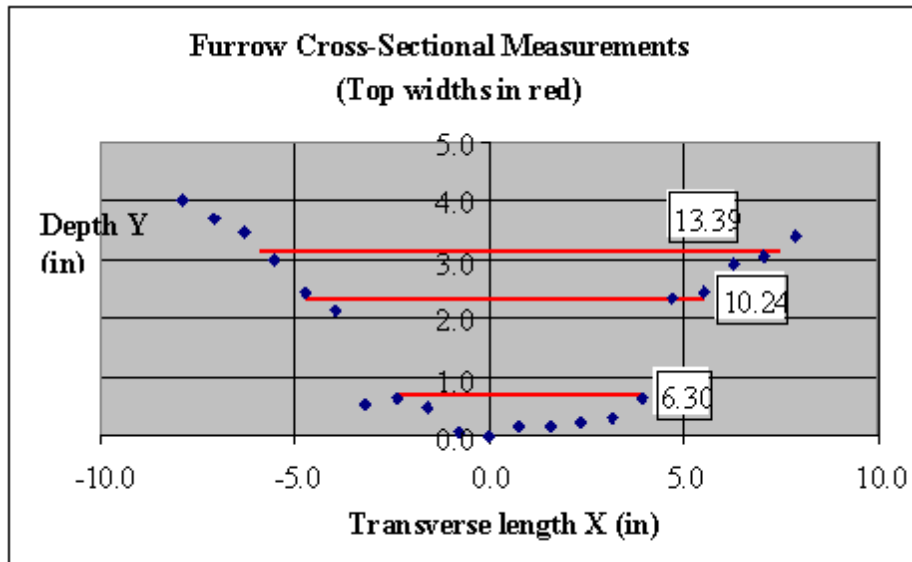
Figure a - Furrow Cross-Sectional Field Measurements

The cross section data can be fitted to either a trapezoid or power law function, as defined by the Furrow Shape option. WinSRFR calculated furrow geometry parameters are displayed in blue but can be modified if a different fit is desired; modified values are displayed in green. Once the desired fit has been achieved, press the "Transfer ..." button to transfer this data back to the WinSRFR Analysis or Simulation. If you have modified any cross section field data, you should choose the "**Save Field Data & Close**" button. The "**Cancel**" button simply closes the dialog box with no further action; any changed values will be lost.

Figure b	**Figure c**
Cross-Sectional Data Entered as Depth / Width Pairs	**Cross-Sectional Data Entered as Profilometer Readings**

This dialog box is accessed using the System Geometry tab. Select either "**Power Law from Field Data**" either "**Trapezoid from Field Data**", then press then "**Edit Data**" button to bring up the dialog box.

4.1.1.2 Slope / Elevation Tables

A field's Slope, specified using the [System Geometry](#) tab, can be a constant value from the start of the field to its end or it can vary with distance down the field. In WinSRFR, Slope is expressed as a constant or as a Slope Table or Elevation Table as shown below. The Slope Table and the Elevation Table are merely different ways of viewing and editing the same tabular data. Only one set of slope data table is stored within WinSRFR for each field. Tabulated Elevation data can be entered and stored then viewed as a Slope Table and vise versa.

Slope Table			Elevation Table		
File Edit			File Edit		
Slope Table			**Elevation Table**		
Distance (m)	Slope (m/m)		Distance (m)	Elevation (m)	
▶ 0	0.0028		▶ 0	10	
25	0.0032		25	9.93	
50	0.0024		50	9.85	
75	0.0036		75	9.79	
100	0.0044		100	9.7	
125	0.004		125	9.59	
150	0.004		150	9.49	
175	0.0052		175	9.39	
Field Length = 625 m			**Field Length = 625 m**		
Vary Slope By ... ⊙ Distance Only ○ Distance & Time			Vary Elevation By ... ⊙ Distance Only ○ Distance & Time		
Ok	Cancel	Help	Ok	Cancel	Help

Operations, such as Copy & Paste and Insert & Delete, are available using either the menu bar or via right-click context menus.

Slope / Elevation Table Dialog Boxes

These dialog boxes allow you to enter tabular data (distance vs. slope or distance vs. vertical elevation) three ways:

- **Manual Entry** – To manually enter data, you will need to add as many rows as needed to the default table (which will open with two rows). Use the Edit/Distances/Insert Rows Before (After) command to add rows. Alternatively, you can right-click the mouse over the leftmost part of the table (the grayed column at the left) to bring up a pop-up menu that will display the insert (and delete) row commands. When entering data, distances must be in increasing order.

- **Import / Export** - You can import values from a text file, using the Dialog's File/Import from Text File command. The file must contain two tab-separated columns of data. You can easily exchange data between projects by using the File/Export to Text File command to export data from an existing WinSRFR project to a text file and then importing those data into the new project.

- **Copy / Paste** – You can import spreadsheet data (Excel, Quattro Pro) using copy and paste. When importing spreadsheet data, existing tabular values will be replaced by the copy/paste operation. Therefore, the spreadsheet data must include at a minimum values at the head and end of the field. You can use copy/paste to transfer data from WinSRFR to a spreadsheet. When importing data, the top row in the spreadsheet data columns can contain unit labels.

NOTE: The grid control used to enter tabular elevation and slope data requires at least two values, at the upstream and downstream end of the field. Those locations cannot be edited. To edit the field length, use the corresponding input box in the Field Geometry Tab.

NOTE: The grid control used to enter tabular data (elevation, furrow cross section, tabulated hygrograph) does not respond to the Enter key when the cursor is at the last row position. Pressing Enter under those conditions will not enter the data. Therefore, when entering the last value (e.g. the last elevation), use the up arrow to move the cursor to the previous row. This will enter the data.

4.1.2 Soil / Crop Properties

The Soil / Crop Properties tab describes the field's hydraulic roughness and infiltration characteristics. Inputs to be provided and choices for those inputs depend on the particular World. Besides entering selections on this tab, two dialog boxes support the definition of the infiltration characteristics:

- Infiltration Formula Matching
- NRCS Intake Family Options

4.1.2.1 Hydraulic Roughness Options

Defining roughness characteristics involves selecting a roughness calculation method and entering the corresponding roughness parameters. Two roughness calculation methods, selected using the Roughness Method drop-down list, are available to all Worlds.

1. User Entered Manning n
2. NRCS Suggested Manning n

Both methods employ the Manning formula to calculate hydraulic resistance. Use the first option to enter a Manning n value; the second option to select from a predefined list of the values suggested by the USDA-NRCS surface irrigation design guides. Use option 1 if locally calibrated Manning n information is available.

The Simulation World offers two additional computational procedures. Both options allow the user to combine the effect of soil hydraulic roughness with vegetation drag and are recommended for advanced users only.

3. Manning n = Cn*Y^An
4. Sayre-Albertson Chi

It should be noted that among the Event Analysis procedures, only the Two-Point Method uses the Manning n in its calculations. The Merriam-Keller approach does not require an n value, but the user needs to provide such an input in order to verify the results via simulation. The Probe Penetration Analysis does not require Manning n either, and the method does not produce infiltration parameters. Still, the user may choose to enter an n value, especially if the underlying data are later copied into the Simulation World for further analysis.

4.1.2.2 Infiltration Options

WinSRFR computes infiltration using a general expression of the form: $Z = z(k,a,...,t\text{-}t_x) * W$

where upper case Z is the infiltrated volume per unit length, lower case z has dimensions volume/length/width and is a function of the empirical infiltration parameters k, a, etc. W is a width (length), t is the time since the beginning of the irrigation and tx is the advance time to a location x. The difference $t\text{-}t_x$ is also known as the opportunity time, τ. In the border and basin case, W is the field width, while for furrows, W is a nominal wetted perimeter. Hence, when working with borders and basins, users need to select an infiltration formula, i.e. the method for computing z, and then enter the corresponding parameter values. When simulating furrow irrigation, users also need to be concerned with defining an approach for calculating W.

WinSRFR offers six infiltration formula choices. In the Simulation World, the choices are:

Name	**Equation Form**
Kostiakov Formula	$z = k\tau^a$
Modified Kostiakov Formula	$z = k\tau^a + b\tau + c$
NRCS Infiltration Family	$z = k\tau^a + c$
Known Characteristic Infiltration Time	$z = k\tau^a$
Time Rated Intake Family	$z = k\tau^a$ with a given by $a = 0.675 - 0.2125\log_{10}(\tau_{100})$
Branch Function	$z = k\tau^a + c, \quad \tau \leq \tau_b$ $z = k\tau_b^a + c + b\cdot(\tau - \tau_b), \quad \tau > \tau_b$ $\tau_b = \left(\dfrac{ak}{b}\right)^{\frac{1}{1-a}}$

After selecting an option, WinSRFR will display input boxes for the corresponding input parameters; the NRCS Infiltration Family selection displays option buttons for selecting a specific NRCS family. When entering infiltration parameter values, care must be taken to ensure that their dimensions and units are consistent. For example, if using the Kostiakov formula, k has dimensions of Length/Time^a while the exponent a is dimensionless. This translates into units of, for example, mm/hr^a if working in metric units, and in/hr^a if working in English units. The units expected by WinSRFR are indicated to the right of each parameter's input box. You can change the units by right-clicking on the units label and selecting the desired units from the context menu.

Some conditions in WinSRFR do not allow all of the above selections. For example, when evaluating an irrigation with Probe-penetration analysis, no infiltration function is determined. When evaluating an irrigation with the Two-Point method, on the Kostiakov and Modified Kostiakov Formula can be used. When working with Furrows in Design or Operations Worlds, users can only select the Known Characteristic Infiltration Time, Kostiakov and Modified Kostiakov Functions.

When simulating furrow irrigation, a value of the nominal wetted perimeter W needs to be specified. WinSRFR's Simulation World offers these choices for calculating this effect, namely:

1. NRCS Empirical Wetted Perimeter
2. Representative Upstream Wetted Perimeter
3. Furrow Spacing
4. Local Wetted Perimeter

WinSRFR selects the NRCS Empirical Function whenever simulating infiltration with the NRCS Infiltration Families. Similarly, the Representative Upstream Wetted Perimeter is used always when the infiltration formula is given by the Time-Rated Infiltration Families. In both cases, the dimensions of the published parameter values are volume per unit length per unit width, so they always need to be multiplied by a wetted perimeter value to compute the correct infiltration volume. For other infiltration formulas, you can compute W with the furrow spacing, representative upstream wetted perimeter, or local wetted perimeter options. Note, however, that this choice is not arbitrary because the parameter values depend on the nominal wetted perimeter used to compute infiltration. For example, WinSRFR's Event Analysis procedures calculate, first, infiltration parameters needed to compute Z (see above equation), and then use the furrow spacing to convert those parameters to their equivalents for computing z (volume/length/width). If the WinSRFR estimated parameters are used in simulation, the user should not arbitrarily change the Wetted Perimeter option to, say, Representative Upstream Wetted Perimeter, as the resulting W, when multiplied z, will not yield the correct value of Z.

This table summarizes the infiltration function and wetted perimeter combinations allowed by WinSRFR:

Infiltration function	Furrow wetted perimeter options
• Kostiakov • Modified Kostiakov • Branch	• Furrow spacing • Representative upstream wetted perimeter • Local wetted perimeter
• NRCS infiltration families	• NRCS empirical wetted perimeter
• Time-Rated infiltration families	• Representative upstream wetted perimeter • Local wetted perimeter
• Characteristic Time	• Furrow spacing

The Simulation World offers an additional option for calculating infiltration. The Enable Limiting Depth option is used in cases where infiltration is limited by a hardpan soil layer. In such cases, cumulative infiltration depth will not increase beyond the user specified value. The input box for the limiting values is enabled whenever the Enable Limiting Depth box is checked. The assumption in using this method is that the user knows what depth of water can infiltrate before the wetting front reaches the hardpan; this is not the depth of the hardpan.

4.1.2.3   Infiltration Formula Matching

Infiltration formula matching occurs whenever the user changes the infiltration formula using the Infiltration Formula drop-down list. The action that follows depends on the option selected under the User Preferences/ Dialogs/ Infiltration Formula. Those options are:

1.   No Matching
2.   Automatic Matching
3.   Confirmed Matching

The No Matching option disables the Match Infiltration Formula mechanism. In this case, the new infiltration formula selection is adopted and the current infiltration parameter values are preserved as displayed in the Soil and Crop Properties Tab. This can cause large differences in infiltration depth vs. time. Further, if the original infiltration formula has more parameters than the alternative equation, the additional parameters are ignored.

Both the Automatic and Confirmed Matching options enable WinSRFR's infiltration formula matching mechanism. This mechanism maps an infiltration equation into an alternative equation (i.e., fits a known infiltration equation with a specific set of parameters to an alternative equation with a different set of parameters, with the alternative equation approximately matching the behavior of the original equation).

When the Automatic Option is enabled, WinSRFR automatically matches the new infiltration formula selection based on the original selection and parameter values. The user has no control over the output and no means for comparing the shape of the original and fitted function.

Enabling the Confirmed Matching option causes WinSRFR to launch the Match Infiltration Method Parameters dialog box, shown below, every time an infiltration formula is chosen using the Infiltration Formula drop-down list. From this dialog box, the user can edit the parameters of the alternative infiltration function until obtaining a desired fit to the original function. At the same time that the Dialog is displayed, the Soil and Crop Properties presents plots of the original and alternative infiltration functions, allowing the user to view the effect of parameter value changes. The matching mechanism is based on the concept of characteristic time, i.e., the time needed to infiltrate a desired target depth z. The Dialog sets z equal to the desired average application depth D $_{req}$, but a different z can be specified, if so desired. Once a desired fit is achieved, the user can press the OK button in the Infiltration Function Matching Dialog to transfer the resulting parameters to the Soil and Crop Properties Tab and close the dialog box. Pressing Cancel will abort the operation and restore the original infiltration function and its parameters.
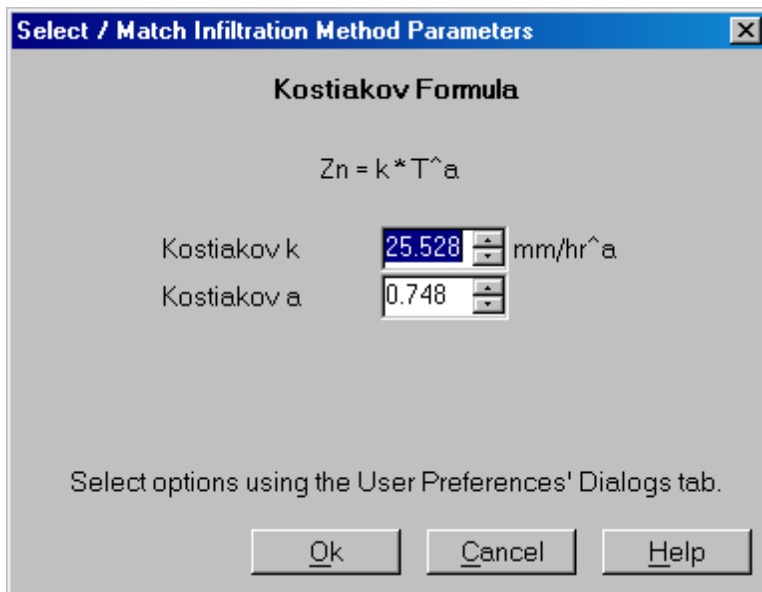
The Match Infiltration Method Parameters dialog box is positioned so the old infiltration method is viewable below the graph and the new method is to the left of the graph. The graph will contain a line for each Infiltration Method. Adjust the parameters of the new Infiltration Method while viewing the results of the change in the graph.

When the new Infiltration Method meets your needs, press Ok to complete the change.

Press Cancel at any time to abort the change.

Note that the infiltration formula matching does not account for nominal wetted perimeter effects in furrows and, therefore, these formula conversions should not be used if they also require a change in the calculation of the nominal wetted perimeter. With furrows, formula matching is allowed only for infiltration formulations that use the same wetted perimeter option, as described in the previous section. The program will issue a warning when attempting a conversion that will invalidate the inputted infiltration parameters.

4.1.2.4   NRCS Intake Family Options

The NRCS Intake Families can cause computational difficulties in the Simulation World when the inflow rate to a field is small relative to the contribution of the c term in the function $z = kt^a + c$. Because of these potential difficulties, WinSRFR allows the user to represent the NRCS Infiltration Families using the standard formulation, or with an approximate fit based on the function $= kt^a$ (c=0). This option is selected using the Options button in the lower-right hand side of the Soil/Crop Properties tab, which is displayed only then the user selects the NRCS Intake Family infiltration option.
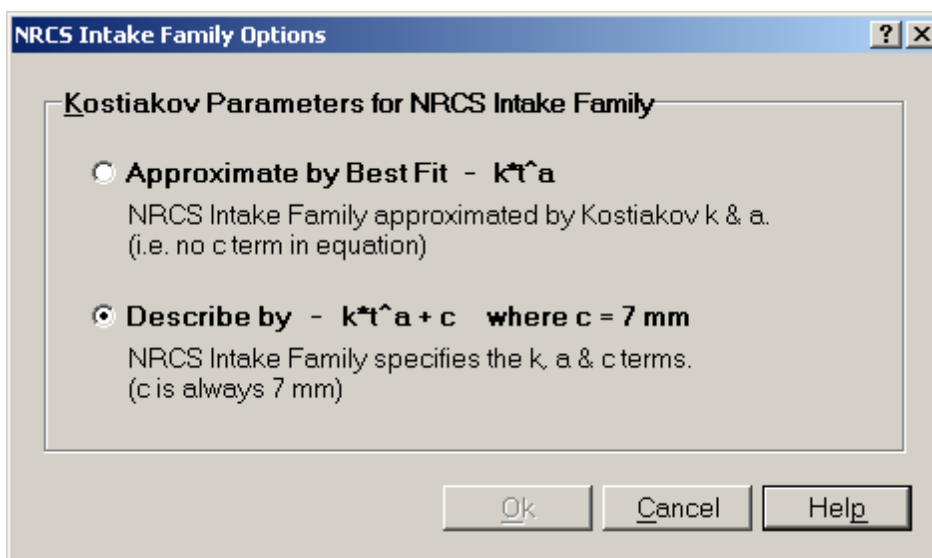
4.1.3   Inflow Management

The Inflow Management tab is used to enter data related to field inflows and outflows. The tab is named Inflow Management when in the Physical Design, Operations Analysis, and Simulation Worlds and in those cases, the tab allows the user to enter only inflow information. In the Event Analysis World, both inflows and outflows are inputs to the analysis and therefore the tab is named Inflow / Runoff. The Simulation World offers various options for specifying the field inflow and only subsets of those options are accommodated by other Worlds. Hence, the following discussion is largely based on the more detailed options available in the Simulation World.

The Inflow Management Tab first provides input boxes for entering the Unit Water Cost (cost of water per unit volume) and the Required Irrigation Depth, D_{req}. Both of these variables are used primarily for post-irrigation performance assessment, but D_{req} is sometimes used to specify inflow options, as will be described further below.

There are two basic approaches for entering inflow information, selectable from the Inflow Method drop-down list. The Tabulated Inflow option allows the user to enter a table of time vs. discharge values. Such an approach should be used when the analysis is attempting to reproduce an observed irrigation event based on a measured, time-varying inflow hydrograph. Hence, 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. Menus 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.

NOTE: Because of array size limitations imposed in the original SRFR simulation engine, the tabulated hydrograph is presently limited to 20 rows of data.

The Standard Hydrograph option allows the user to specify simple inflow hydrographs, for example a constant inflow rate with a prescribed cutoff time, but the selection also enables some relatively advanced input options. Upon selecting Standard Hydrograph, WinSRFR displays an input box for the Inflow Rate Q, and frame boxes that are used to specify cutoff and/or cutback options. The inflow rate is assumed constant, unless cutback options are specified. Available cutoff options for the simulation world are:

1. Time-based cutoff – Cutoff occurs at the user-specified cutoff time Tco, 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.
2. Distance-based cutoff – Cutoff occurs at a prescribed Cutoff Location Xco, expressed as a function of the field length L (Xco = R * L). This location is the position of the advancing stream front.
3. Distance and Infiltration Depth – Cutoff occurs when a given infiltration depth *z*, expressed as a fraction of Dreq (z = Rz * Dreq) has accumulated at a prescribed downstream Cutoff Location (Xco = 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.
4. 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 (Xco = R * L).
5. 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.

In the design and operations worlds, only time-based cutoff is allowed.

Cutback options are:

1. No Cutback - This is the default selection for the Standard Hydrograph.
2. Time-Based Cutback – Inflow rate is reduced at the specified Cutback Time and to the Cutback Rate Qcb, expressed as a function of the initial Q (Qcb = RQ * Q)
3. Distance-Based Cutback - Inflow rate is reduced when the advancing stream reaches the specified Cutback Location to the specified Cutback Rate.

Note that the time-based cutback option depends on cutoff time and, therefore, is undefined when using any distance-based cutoff. In the design and operations worlds, no cutback is allowed for borders/basins, and only time-based cutback is allowed for furrows.

Outflow data are a required input in the Event Analysis World, but only for systems with an open-end downstream boundary condition. Outflow can be specified only as a tabulated hydrograph. Like the inflow data, data entry is either manual, from a text file, or by using copy/paste.

4.1.3.1 Inflow / Runoff Tables

An irrigation's inflow rate, specified using the [Inflow Management](#) tab, can be entered using a Standard Hydrograph as shown above or using an Inflow Table as shown below. Runoff, if it is required, can only be specified as a Runoff Table.

Operations, such as Copy & Paste and Insert & Delete, are available using either the menu bar or via right-click context menus.

4.2 Analysis of Irrigation Events (Field Evaluation)

The process of improving the performance of surface irrigation systems typically starts with an evaluation of current performance based on field-measured data. The evaluation's primary purpose is to describe the fate of the applied water, but it can also yield estimates of a field's infiltration and/or hydraulic roughness characteristics, which are key inputs for subsequent analyses. The evaluation helps identify performance problems, and whether those problems are related to the lack of an overall water-management strategy (no target, application that grossly deviates from the intended target, etc.) and/or to hydraulic operation and/or design.

If performance problems are related to system hydraulics, then alternatives for optimizing the operation of the existing system need to be examined first. If the optimized operation still results in unacceptable performance, then changes to the existing design have to be explored. Both operational and design analyses have to be conducted based on practical ranges of the operational or design decision variables. Furthermore, while recommendations need to target the anticipated average conditions under which the system will be operated, they also need to account for potential variations in field conditions from those assumed in the analysis, including changes in infiltration and roughness characteristics, inflow rate, bottom slope non-uniformities, etc. Sensitivity analyses need to be conducted and adjustments made to the operational/design recommendation to assure reasonable levels of performance considering these potential variations.

The Event Analysis World provides tools for summarizing, graphing, and analyzing field evaluation data. Users can assess the performance of an observed irrigation event and estimate the parameters of the empirical infiltration functions used by the simulator. At this time, WinSRFR provides these evaluation procedures:

a) Probe Penetration Analysis - post-irrigation volume balance based on a measured infiltration profile (which requires probe penetration data, water holding characteristics of the probed soil profile, and estimates of soil water content)

b) Merriam-Keller Analysis - post-irrigation volume balance from advance and recession measurements (based on Merriam-Keller and NRCS procedures)

c) Elliot-Walker Two-Point Analysis - advance phase volume balance (based on Elliott and Walker's two-point method).

d) Erosion Parameter Estimation - estimate parameters necessary to simulation erosion.

4.2.1   Probe Penetration Analysis

Overview

This procedure, accessed by selecting the *Probe Penetration Analysis* option in the Event Analysis Tab, determines the depth of water infiltrated during an irrigation event by measuring the depth of the wetted soil profile with a metal probe. The wetted soil profile length is converted into a depth of water based on the water holding characteristics of the soil and the pre-irrigation water deficit. The probe will easily penetrate the saturated soil but not the dry/unsaturated soil. The approach works better with heavy to medium soils than in light soils. These evaluations cannot determine deep percolation losses unless the probed depth is much greater than the root zone depth or, alternatively, the total infiltrated depth can be calculated from a final mass balance based on inflow and outflow measurements.

Applicability

This methodology is applicable to all types of systems, and with any type of downstream boundary condition. In border/basin irrigation, the assumption is that the infiltrated profile is uniform across the width. With furrows, the wetted profile depth will be different below the furrow top than below the bottom so probe measurements need to be taken at both locations to determine an average penetration depth. Since infiltration parameters are not determined with this procedure, insufficient information is provided for further analysis in WinSRFR. (That is, the user cannot perform operation evaluation, design, or simulation). Thus it is not useful for providing quantitative recommendations for improvement.

4.2.1.1   Inputs

Common data

Common data requirements are summarized in the following tables. Not all data provided in these tables are required to complete an analysis. If the data are intended to be used in subsequent simulation, design, or operations analyses, then the recommendation is to enter the unused inputs, for completeness. This will ensure the consistency of data for all scenarios developed from the original evaluation scenario.

System Geometry tab

Input	Required	Use
Length	Yes	Calculation of the infiltrated profile from the probe measurements
Width	No	Calculation of the final mass balance; if mass balance data are not provided, the Width is not used
Overflow depth	No	None
Slope	No	None

Soil / Crop Properties tab

Input	Required	Use
Hydraulic Roughness	No	None
Infiltration	No	None (disabled)

Inflow / Outflow tab

Input	Required	Use
Inflow	No	Calculation of final mass balance
Outflow	No	Calculation of final mass balance

If inflow/outflow data are not given, a final volume balance will not be calculated and deep percolation losses will not be estimated. These data do not affect the calculation of the infiltrated profile.

Distance-based cutoff and cutback options are not applicable in Event Analysis and, therefore, are disabled. Time-based options are still valid.

Probe Measurements tab

The probe measurement tab, illustrated in the figure below, consists of the three sections:

- Soil Water Depletion (SWD) Table
- Irrigation Target Calculation Section
- 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[1]. 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 need to be combined into a single set of values. The table consists of seven columns, four of which are for inputs and three for outputs. Three of the input columns are required, but one is not. The AWC can be determined from soil physical measurements or estimated from published values[2]. The Soil Water Deficit (SWD) is measured from soil samples extracted with an auger. For conventional field studies, SWD can be estimated using the procedures described in USDA-NRCS (1998)[3].

Variable	Input or Output	Required?	Description
Profile depth	input	yes	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	no	Soil textural description. This field is used only for descriptive purposes, not in the calculations
AWC	input	yes	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 related soil texture to AWC.
SWD	input	yes	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 can be estimated using the touch and appearance method (ref)
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.

Note: WinSRFR tables will not recalculate until you switch focus from the current cell to a different cell in the table or to another control on the form. After editing a cell, use the TAB or ?,?, ?, ? keys to force the table to recalculate.

Irrigation Target Calculation section

The Irrigation Target Calculation Section determines the irrigation requirement, taking into account the soil water deficit and leaching needs. Two inputs need to be specified to make this calculation, the Root Zone Depth and the Leaching Fraction. The Leaching Requirement (a depth) is the product of the fractional fraction and the Root Zone SWD. The Irrigation Target Depth is the irrigation requirement, the sum of Root Zone SWD and Leaching Requirement.

In typical evaluations, the cumulative soil profile will be equal to the root zone depth and, the Root Zone SWD will then be equal to the deficit calculated in the SWD table. The Root Zone SWD will be less than the cumulative SWD only in cases where the cumulative soil profile is deeper than the root zone. In those cases, deep percolation losses can be estimated. The root zone deficit cannot be fully determined if probed soil profile is shallower than the depth of the root zone. Similarly, the root zone deficit cannot be calculated if the user does not provide a root zone depth. For crops with deep root zones but where the only the upper soil layers are used to manage irrigation water, then the root zone depth can be defined based on the depth of the management layer.

The Irrigation Target Calculation Section also displays an input text box for the Probe Length. This value is used for post-irrigation depth calculations, explained in the next section. The probe should be longer than the root zone depth, otherwise the root zone infiltrated depth will be underestimated. The program will issue warnings in such cases.

The Warning Box will alert the user to potential problems or inconsistencies with the inputs provided to the pre- or post-irrigation tables. Additional warning/error messages are provided in the Execution Tab.

Post-Irrigation Infiltrated Depths table

The Post-Irrigation Infiltrated Depths table (ID Table) consists of six columns two of which are required inputs, and four computed values, which are defined in the following table.

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

Based on 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 may be able to estimate the depth of water contributing to the leaching requirement, and the depth of percolation losses.

_____

[1] USDA-NRCS Irrigation Guide (1997), exhibit 9-2

[2] see for example Saxton, K. 2006 the Soil Water Characteristics - Hydraulic Properties Calculator. USDA-ARS/Washington State University

[3] USDA-NRCS. Estimating Soil Moisture by Feel and Appearance. Program Aid no. 1619. April 1998

4.2.1.2   Execution

Execution Tab

All calculations needed for this analysis are conducted as the user enters the needed data in the Probe Measurements Input Tab. The Execution Tab has only one input control, the Summarize Analysis button. The only function of this button is to prompt the program to generate all printable output forms. The tab will also display warning messages, to indicate possible problems with the analysis due to the nature of the data, or error messages when required data is missing or inconsistent. The analysis will not be completed if errors are detected in the data.

4.2.1.3   Outputs

Outputs generated by the Probe Penetration Analysis are described in the following table.

Output Tab Name	Type	Description
Input Summary	Table	Summary of geometry, crop and soil properties, and boundary conditions
Soil water deficit (SWD)	Table	Same table as the SWD table in the Probe measurement tab
Infiltrated depth (ID) inputs	Table	Same table as ID table in the Probe measurement tab
Performance analysis table	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	Graph	Inflow-outflow hydrographs. Generated if the data are provided
Infiltration depths	Graph	Displays the root zone deficit, the irrigation requirement, and the measured root zone and useful infiltrated depths

4.2.1.4   **Example**

This example corresponds to "Scenario 1", found in example file "Infiltrated Profile Analysis Examples.srfr".

A summary of the input data can be viewed from the Input Summary tab sheet (not shown here). Part of the Soil Water Depletion output tab sheet is displayed in above screenshot. The SWD is calculated using three soil layers, each with different textural properties, and therefore with different AWC. The table calculates the SWD for individual soil profiles, and then the total SWD for 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 can yield the root zone deficit prior and subsequent to the irrigation. The analysis can also yield the depth of contributing to the leaching requirement, although not in its entirety because the irrigation target is 82 mm (75 mm of Root Zone SWD 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 as NaN (Not a Number).

The analysis shows that the root zone was refilled except at the downstream end of the field where a small deficit was measured, while leaching requirements were likely met only at the upper end of the field. While deep percolation losses cannot be quantified directly from the probe data, they are estimated from the final mass balance analysis (input and outflow data are provided for this example). The example file provides two additional scenarios for which a final mass balance cannot be calculated. The user is encouraged to change the depth of the soil profiles included in the SWD table, the root zone depth, and the probe length, and view the effect of those changes on the results in either one of these scenarios.

```
WinSRFR 3.0.15 - Border - Measured infiltration profile data (probe penet...  [_][□][X]

File   Edit   View   Evaluation   Help

💾 🖨  ↺ ▾ ↻ ▾  ⤷ ▮ ♣?                                                            ➕

        Farm: Event Analysis Examples, Field: Tests
        Folder: Irrigation Evaluations, Analysis: Infiltrated Profile Analysis

Field Measurements | Irrigation Requirements | Infiltrated Depths | Inflow & Runoff | Infiltrated Depths | Performance Analysis

        WinSRFR 3.0.15 - Arid-Land Agricultural Research Center, Maricopa, AZ
            Event Analysis Results - Thursday, December 18, 2008 10:43 AM


                Farm: Event Analysis Examples, Field: Tests
        Folder: Irrigation Evaluations, Analysis: Infiltrated Profile Analysis


    Probe Measurements & Infiltrated Depths

    Probed Infiltrated Depths Table (Post-Irrigation Measurements)


                        |-------- Infiltrated Depths --------|
    Distance  Probe Depth  Profile  Root Zone  Leaching  Useful  Deep Perc.
    (m)       (m)          (mm)     (mm)       (mm)      (mm)    (mm)
    --------  -----------  -------  ---------  --------  ------  ----------
    0         1.4          81       75         6#        81#     NaN
    25        1.4          81       75         6#        81#     NaN
    50        1.35         80       75         5         80      0
    75        1.35         80       75         5         80      0
    100       1.25         76       75         2         76      0
    125       1.2          75       75         0         75      0
    150       1.15         73       73         0         73      0
    175       1            68       68         0         68      0


    Average Probed Infiltrated Depths
        Root Zone Depth:     74 mm    56.1 %    $15.50
      + Leaching Depth:       3 mm     2.3 %     $0.63
         = Useful Depth:     77 mm    58.3 %    $16.13
      + Deep Percolation:     0 mm
      = Infiltrated Depth:   77 mm    58.3 %    $16.13

Event World | System Geometry | Soil Crop Properties | Inflow / Runoff | Probe Measurements | Execution   Results

Results are available; View using the Results tab                          User Level: Advanced
```

4.2.2 Merriam-Keller Post-Irrigation Volume Balance

Overview

This procedure is accessed by selecting the *Measured Advance and Recession Data* Option Button in the Event Analysis Tab.

The methodology uses advance and recession times measured at stations along the field to determine the infiltration opportunity time. These opportunity times are then used in a post-irrigation mass balance to estimate an infiltration function for the field. WinSRFR represents the infiltration process with empirical equations and offers several choices for fitting the data. The estimated function is used with the measured opportunity times to estimate the infiltration profile and irrigation performance.

Applicability

This methodology is applicable to all types of systems, and with any type of downstream boundary condition.

4.2.2.1 Inputs

Common data

Common data requirements are summarized in the following tables. Note that not all data provided in those tables are required to complete an analysis. If the data will be used in subsequent simulation, design, or operations analyses, then the recommendation is to enter the unused inputs, for completeness. This will ensure the consistency of data for all scenarios developed from the original evaluation.

System Geometry tab

Input	Required	Use
Length	Yes	Calculation of the infiltrated volume
Width/Set Width	Yes	Calculation of the final mass balance
Overflow depth	No	None
Slope	Yes	With furrows, used to determine the wetted perimeter when using fitting the NRCS and Time-Rated infiltration families; also needed for validation (used by the simulation engine)

Soil / Crop Properties tab

Input	Required	Use
Hydraulic Roughness	Yes	With furrows, used to determine the wetted perimeter when using fitting the NRCS and Time-Rated infiltration families; also needed for validation (used by the simulation engine)
Infiltration	No	Output generated by the method

Inflow / Outflow tab

Input	Required	Use
Inflow	Yes	Calculation of the final volume balance
Outflow	Yes	Calculation of the final volume balance

Distance-based cutoff and cutback options are inapplicable with this procedure and are disabled. Time-based cutoff and cutback options are still valid.

Advance-Recession tab

Advance and recession data are entered through two tables in the Advance and Recession Tab page, illustrated below. Data are entered as a time series (distance vs. advance/recession time). A third table displays the calculated Opportunity Times. In typical Merriam-Keller evaluations, the same distance values are used to measure advance and recession times. If advance data are provided at different distances than the recession data, WinSRFR will calculate the opportunity times at all the given distances and interpolate 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 (see Data Table Entry for details on how to work with WinSRFR tables). 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 end 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, determining an advance time to a given station can be difficult in those types of systems. For those cases, the user can try to estimate the fraction of wetted border/basin as a function of time and use those values as surrogates of advance distance.

4.2.2.2   Execution

Execution Tab

This tab, illustrated below, displays five sections:

- Select Infiltration Function
- Solution
- Run control
- Errors and Warnings
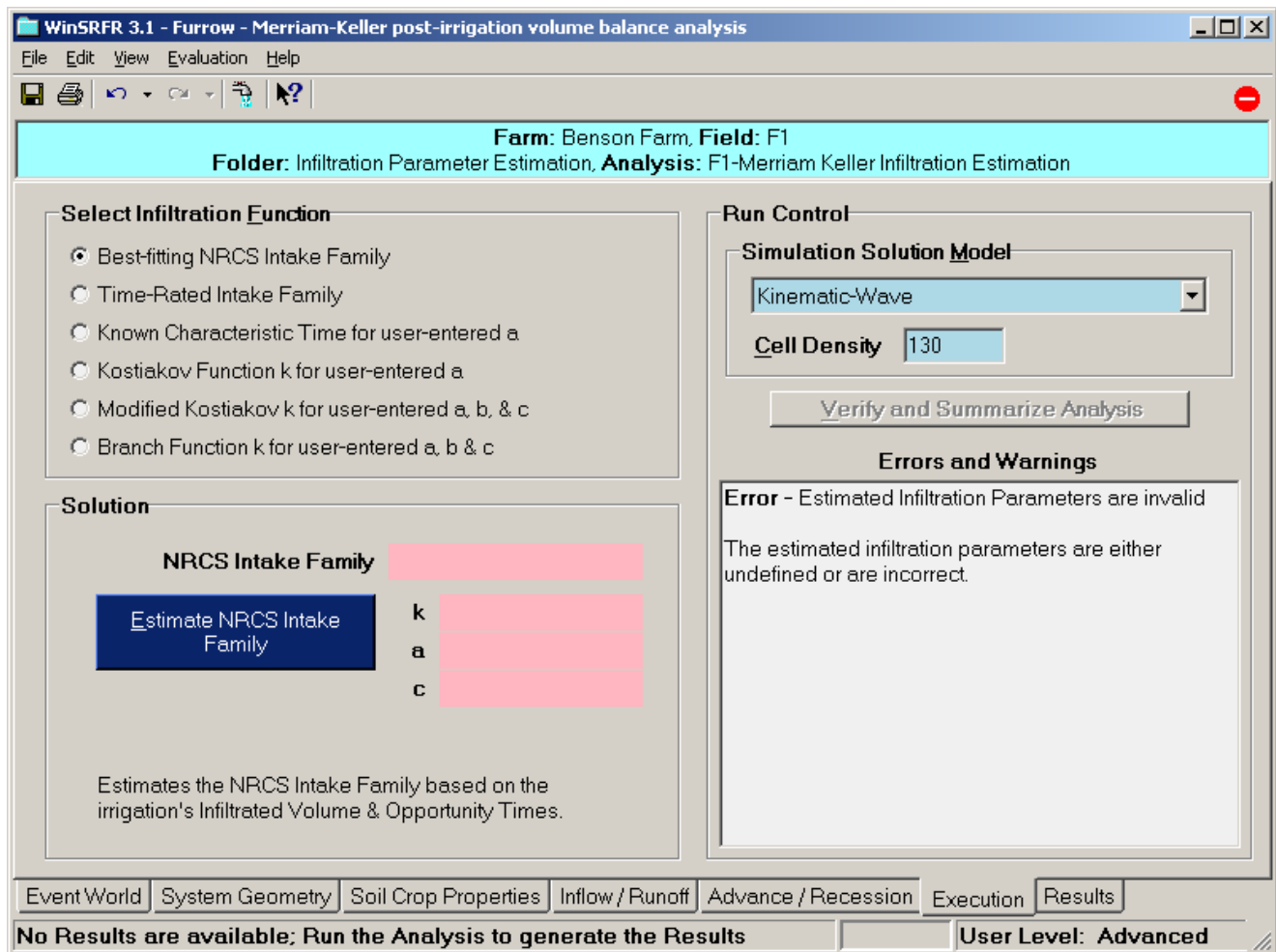
The Infiltration Functions option buttons select the infiltration equation to be used in formulating the post-irrigation volume balance. This choice will affect the number of parameters that the user will have to estimate independently and provide as an input to the program. Infiltration function choices, required parameter inputs, and the resulting parameter estimates are displayed in the following table:

Infiltration Function Options

Infiltration option	Required inputs	Estimated parameters
NRCS Intake Families	None	Infiltration family (k, a)
Time Rated Intake Families	None	Infiltration family t_c (k,a)
Known characteristic infiltration time	a	k (z_c, t_c)
Kostiakov Function	a	k
Modified Kostiakov Function	a, b, c	k
Branch Function	a, b, c	k

When dealing with infiltration families, the program determines the two needed parameters. For all other infiltration functions, the program only calculates the constant k. When using the Characteristic Time function, WinSRFR will use the user-specified target depth as the characteristics depth z_c. WinSRFR will then calculate the characteristic time t_c based on z_c, the user specified a, and the program-calculated k.

These infiltration function choices apply to any irrigation system type. In WinSRFR, all furrow infiltration calculations require selecting an infiltration formula and also a wetted perimeter effect option. While the Simulation World (see Hydraulic Simulation/Common Inputs) offers several wetted perimeter effect choices for a given infiltration function, for estimation the choices are restricted to the combinations shown in table below. Hence, selection of the wetted perimeter option handled by the software, without user intervention.

Infiltration function	Wetted perimeter option
NRCS Intake Families	NRCS empirical wetted perimeter
Time Rated Intake Families	Representative upstream wetted perimeter
Known characteristic infiltration time	Furrow spacing
Kostiakov Function	
Modified Kostiakov Function	
Branch Function	

The Solution section of the Execution Tab sheet is configured differently depending on the Infiltration Function choice and, therefore, on the parameters that must be provided as inputs. These inputs are provided through input control boxes, coded in green. A calculation button Accept .. (blue) forces the program to calculate k and related parameter(s) for the current inputs; results are displayed in the pink-coded output boxes.

The input button Verify and Summarize is used to, first, request the program to validate the estimated function and, second, to summarize the analyze and generate all pertinent output forms. This button will be disabled until all necessary data are provided. The program will display a message in the Errors and Warning message box whenever it detects problems with the data.

Validation is performed by conducting an unsteady flow simulation. Simulation results are then compared with the observations. The Run Control model displays two controls that affect the validation simulation run. These controls cannot be modified by a Standard User but can be modified by an Advanced user. These controls select the simulation engine and the number of computational cells used in those calculations. In most cases, the

user will not have to modify WinSRFR's selections for these variables. However, for cases where the validation simulation fails, the user may need to edit these choices, if allowed by the data. More details on the use and limitations of these options is provided in the Hydraulic Simulation section.

WinSRFR generates several outputs that can be used to compare the simulation results with the field measured data and evaluate the goodness-of-fit of the estimated function. Differences between the predictions and observations can be reduced by adjusting the user-entered infiltration parameters and/or by selecting of an alternative infiltration function. For example, when using the Kostiakov equation , the user needs to provide a value for the exponent a. In the original Merriam-Keller methodology, this value was measured with ring infiltrometer tests. In the absence of such measurements, the user may chose to test reasonable values of a until finding one that gives a good match between observations and predictions. Experience, published information, and judgment should be used in selecting a range of values of a to test, and in making adjustments to parameters because a set of parameters that minimizes the differences between observations and predictions may not necessarily provide a realistic representation of the infiltration process. Referring again to the Kostiakov infiltration function example, a best fit can sometimes be found with a near-zero value for the exponent a. Such a small value of the exponent implies an infiltration rate that goes almost instantaneously to zero. The evaluator has to decide whether such a function represents the process realistically, whether the results are related to troublesome data, or whether a different infiltration model needs to be adopted.

A major difficulty in making adjustments to the infiltration function is that other inputs required for estimation and validation (e.g., hydraulic roughness) may also be uncertain. Therefore, the analysis may also require conducting sensitivity tests for those other uncertain parameters, in addition to the user-entered infiltration parameter estimates.

4.2.2.3 Outputs

Outputs generated by the analysis are the following.

Output Tab Name	Type	Description
Input Summary	Table	Summary of common inputs
Estimated Function	Table	Summary of advance-recession data and estimated infiltration function
Performance Analysis	Table	Efficiency and uniformity indicators, based on the estimated function and the observed opportunity times
Goodness-of-fit	Table	Statistics computed from observations and simulation results
Inflow & Runoff	Graph	Inflow and outflow hydrographs (time vs. discharge)
Advance/Recession	Graph	Advance and recession trajectories (distance vs. time)
Infiltration Function	Graph	Estimated infiltration function (time vs. depth)
Infiltrated Depths	Graph	Infiltration profile, computed from the measured opportunity times and the estimated function, and average infiltrated depth (from volume balance)

4.2.2.4 Example

An example can be found in the file Merriam-Keller Analysis Examples.srfr.

The example's data were reported by Elliott (198?) as Benson Farm, Irrigation 2, Group 2, Furrow 5 (Benson 2-2-5). The data set includes advance and recession data measured at 25 m intervals, field elevations at each of these advance measurement stations, cross-sectional data measured with a profilometer at about 100 m intervals, and inflow and outflow hydrograph. Because these hydrographs were not measured until final cutoff and runoff times, respectively, these times were assumed based on the measured recession data. The analysis assumes a prismatic channel so the cross-sectional measurements were averaged and used to define the geometrical parameters (see section Fitting furrow cross-sectional data).

The Event Analysis folder Folder 1 contains three scenarios based on the Benson 2-2-5 data. Each scenario is based on a different formula selection, the NRCS Infiltration Families, the Time-Rated Infiltration families, and the modified Kostiakov equation. A different wetted perimeter option also applies to each of these infiltration function choices, as explained earlier. The post-irrigation volume balance problem has a unique solution when formulated in combination with the NRCS or Time-Rated families (because the parameters of those functions are pre-determined and uniquely related to each other) but has multiple solutions when formulated in combination with the Modified Kostiakov equation. The Modified Kostiakov solution given in the example file is one of many possible solutions. Other solutions can be found by modifying the values of the parameters a,b, and c, which in turn will produce a different value for k. While the parameters have in principle no physical meaning, they should provide a realistic representation of the infiltration process and must be chosen judiciously, as explained earlier.

The resulting infiltration functions and validation results can be inspected from the output tabs for each scenario. However, instead of analyzing those results individually, we can use the Data Comparison tool (Tools/Data Comparison) to compare estimation results with each other and with the field data (Figure XX). To make these comparisons, simulation scenarios were generated from each of the estimated infiltration functions, by copying the event scenarios and pasting them into the simulation folder Folder 1. They can then be selected for display with the Data Explorer Control of the Comparison Tool.

The figures below illustrate key comparisons that can be conducted with the Data Comparison tool:

- Advance and recession trajectories
- Inflow and runoff hydrographs
- Upstream infiltration
- Final infiltration profiles

The estimated functions predict the observed, recession, and runoff data with different degrees of accuracy, even though all of them satisfy the post-irrigation volume balance relationship. Advance and runoff predicted with the Modified Kostiakov solution is closest to the observed values. The average infiltrated depth simulated with the Modified Kostiakov function is also the one that most closely matches the average infiltrated depth measured on the field. Note that because the estimated functions use a different wetted perimeter option to calculate the infiltration volume per unit length, they need to be compared on the basis of the Upstream Infiltration (see section XX). This graph shows that the estimated functions differ mostly in the resulting infiltrated depth at short times.

WinSRFR Data Comparer tool showing Advance & Recession Trajectories
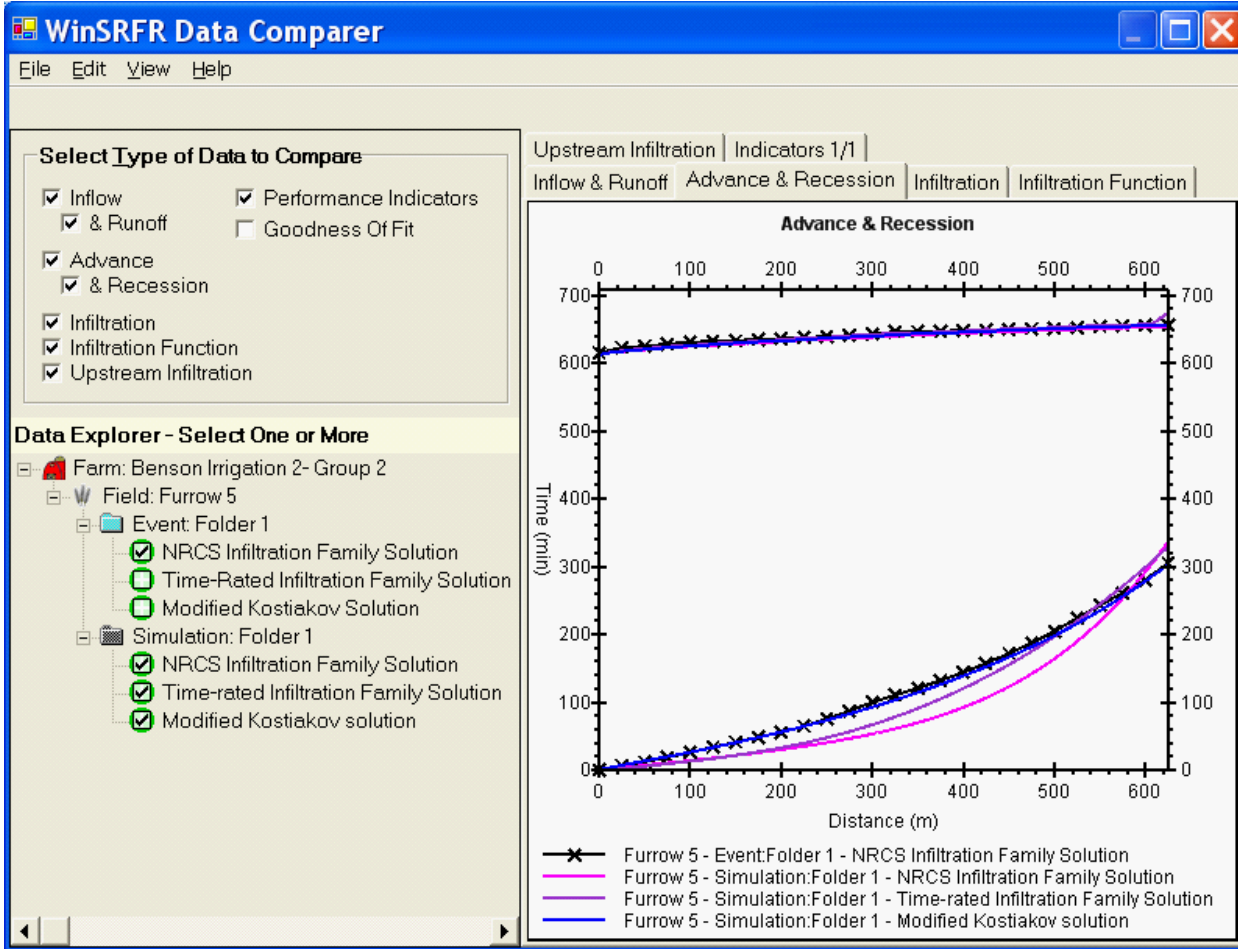
Inflow & Runoff Hydrographs
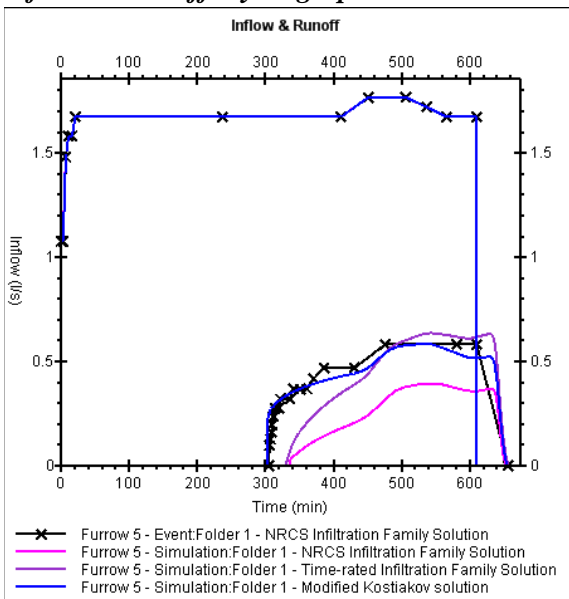
Upstream Infiltration
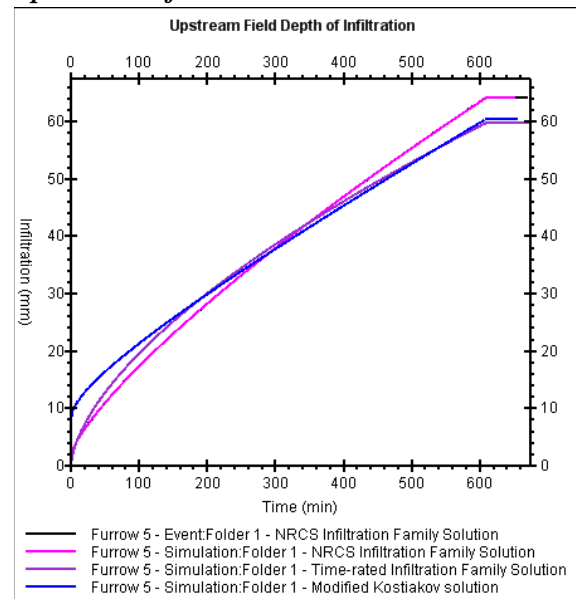
Final Infiltration Profile
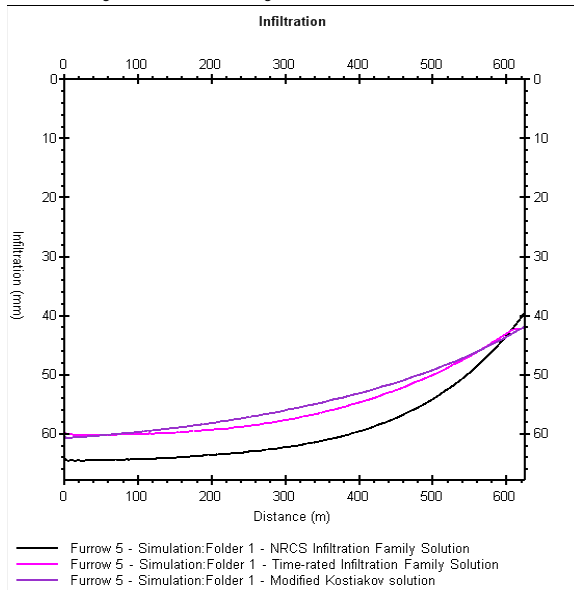
The estimated infiltration functions are uncertain because of the uncertainty of the inputs and the inherent variability in time and space of infiltration properties. These and other potential results can be used to frame the range of likely infiltration conditions for the problem. Performance analysis results should be interpreted with caution because of the uncertainty of the infiltration estimates. Similarly, subsequent operational and design analyses need to be conducted taking into account the uncertainty of the estimation results.

When validating the Merriam-Keller solution, output errors generated by simulation engine will occasionally prevent WinSRFR from completing the goodness-of-fit analysis. Such problems can occur, for example, when inflow is not constant with time or when variable field elevations are specified. For those cases, the analysis can still be completed manually, by copying the scenario into a simulation folder, performing an unsteady simulation with the estimated function, and then comparing the observed and predicted results using the data comparison tool (the comparison tool will generate goodness-of-fit measures when comparing measured and predicted data).

4.2.3   Two-Point Analysis

Overview

This procedure is accessed by selecting the *Two-Point Data* Option Button in the Event Analysis Tab.

The methodology uses advance times measured at two stations along the field (generally the mid-point and end-point) to estimate an infiltration function for the field. The procedure assumes that infiltration can be represented by the Modified Kostiakov infiltration equation: $z = kt^a + bt$. The estimated function is used to simulate the irrigation event and to estimate the infiltration profile and irrigation performance. For furrows, the infiltration depth is multiplied by furrow spacing to obtain a volume per unit length of furrow.

Applicability

The procedure was developed for sloping, open-ended furrows. The method can produce reasonable estimates when the surface storage volume is very small relative to the infiltrated volume at the time that advance is measured. Therefore, it is not recommended in general for other types of surface irrigation systems and needs to be cautiously even with sloping furrows.

4.2.3.1   Inputs

Common Data

Common data requirements are summarized in the following tables. Note that not all data provided in those tables are required to complete an analysis. If the data will be used in subsequent simulation, design, or operations analyses, then the recommendation is to enter the unused inputs, for completeness. This will ensure the consistency of data for all scenarios developed from the original evaluation.

System Geometry tab

Variable	Input / Output	Use
Length	Input	Calculation of the infiltrated volume during advance
Width/Set Width	Input	Calculation of the final mass balance during advance
Overflow depth	Input	Not required, used by the validation simulation
Slope	Input	Needed for validation

Soil / Crop Properties tab

Variable	Input / Output	Use
Hydraulic Roughness	Input	Needed for validation
Infiltration	Output	Output generated by the method

Inflow / Outflow tab

Variable	Input / Output	Use
Inflow	Input	Calculation of the applied volumes at the measured advance times
Outflow	input	Calculation of final infiltration rate, if selected. Comparison to measured outflow.

Distance-based cutoff and cutback options are inapplicable with this procedure and are disabled. Time-based cutoff and cutback options are still valid.

Two-Point Advance tab

Two advance distance-advance time pairs need to be specified in this tab. The recommended approach is for the advance time measurement stations to be located halfway and at the full field length. The form displays a few intermediate results that can be used to detect possible data anomalies.

4.2.3.2   Execution

Execution Tab displays three sections:

- Two point solution
- Run control
- Errors and Warnings

Estimates of the Modified Kostiakov parameters k and a are computed in the two-point method based on user-provided values of the steady-infiltration rate parameter b and the surface shape factor $_y$. Estimates of b may be available from past experience or alternative measurements. For open-ended fields with runoff measurements, the user can request the software to generate an estimate of b. This value is calculated as:

$$b = \frac{(\bar{Q}_{in} - Q_{ro}(t_{co}))}{2 * L * W}$$

Where $\bar{Q}_{in}$ is the average inflow rate, $Q_{ro}(t_{co})$ is the outflow rate measured at cutoff time, L the field length and W the width (in the case of furrows, the furrow spacing). The surface shape factors $_y$ are needed as part of the mass balance calculations, in particular to determine the surface volume at the given advance times. The software assigns a default value 0.76, but the user can edit those values. For typical calculations, this value should be in the range $0.5 < {}_y < 1.0$. The original two point method uses normal depth at the upstream end. For mild slopes, normal depth is approach only very gradually, or not at all in the case of zero slope. WinSRFR uses a zero-inertia representative upstream depth. For steep slopes, it is very close to normal depth, but deviated substantially for shallow slopes. Unlike the original two-point method, this upstream representative changes with advance distance. WinSRFR also allows the surface shape factor to be different for the two advance times. The two-point analysis output tab page displays upstream water depths and shape factors extracted from the validation simulation. Those simulation results can be used to compare the upstream water depths and to update the user entered values of $_y$. The input button **Estimate a & k** prompts the program to calculate the infiltration parameters.

The input button Verify and Summarize is used to, first, request the program to validate the estimated function and, second, to summarize the analyze and generate all pertinent output forms. This button remains disabled until all needed inputs are provided. The program displays messages in the Errors and Warning message box whenever it detects problems with the data.

The estimated infiltration function is validated by conducting an unsteady flow simulation and comparing the simulation results with the observations. Validation results may suggest adjustments to the steady-infiltration parameter b or the shape factors. Judgment needs to be used in making those adjustments as they may result in an unrealistic representation of the infiltration process (e.g. negative parameters).

The Run Control model displays two controls that affect the validation simulation run. These controls cannot be modified by a Standard User but can be modified by an Advanced user. These controls select the simulation engine and the number of computational cells used in those calculations. In most cases, the user will not have to modify WinSRFR's selections for these variables. However, for cases where the validation simulation fails, the user may need to edit these choices, if allowed by the data. More details on the use and limitations of these options is provided in the Hydraulic Simulation section.

A major difficulty in making adjustments to the infiltration function is that other inputs required for estimation and validation (e.g., hydraulic roughness) may also be uncertain. Therefore, the analysis may also require conducting sensitivity tests for those other uncertain parameters, in addition to the user-entered infiltration parameter estimates.

4.2.3.3 Output

Outputs generated by the Two-Point Analysis are the following:

Output Tab Name	Type	Description
Input Summary	Table	Summary of common inputs
Estimated Function	Table	Summary of advance-recession data and estimated infiltration function
Parameters & Goodness-of-fit	Table	Efficiency and uniformity indicators, based on the estimated function and the observed opportunity times. Statistics computed from observations and simulation results
Inflow & Runoff	Graph	Inflow and outflow hydrographs (time vs. discharge)
Two-point advance	Graph	Advance and recession trajectories (distance vs. time)
Infiltration Function	Graph	Estimated infiltration function (time vs. depth)
Infiltrated Depths	Graph	Infiltration profile, computed from simulation with the estimated function

4.2.3.4   Example

An example can be found in the Two-Point Analysis.srfr file.

The example was reported by Elliott (1980), test Matchett Irrigation Number 2, Group Number 3, Furrow 5 (Matchett 2-3-5). The evaluated furrow is 425 m long and has an average slope of nearly 0.1%. Furrow geometrical parameters were calculated from profilometer measurements included in the data set (see section Fitting furrow cross-sectional data). Advance times were measured at 25 m intervals; the advance times measured at 200 m and 425 m were used for the example's calculations.

The data set also includes a complete runoff hydrograph. These data were used to compute an initial estimate for the parameter b, using the procedure provided by the program. An estimate for the parameters k and a were then calculated based on the default parameters for $_y$.   After completing the analysis, the shape factor values were updated based on the output displayed in the Two-Point Advance tab sheet and a new set of parameters were calculated.

The figure below compares the measured and predicted runoff hydrograph. Results presented in the Parameters and Goodness-of-Fit tab sheet, not shown here, show that the estimated function reproduces all measured components of the irrigation event accurately. Thus, the infiltration properties of the evaluated field appear to be reasonably well represented by the estimated function.
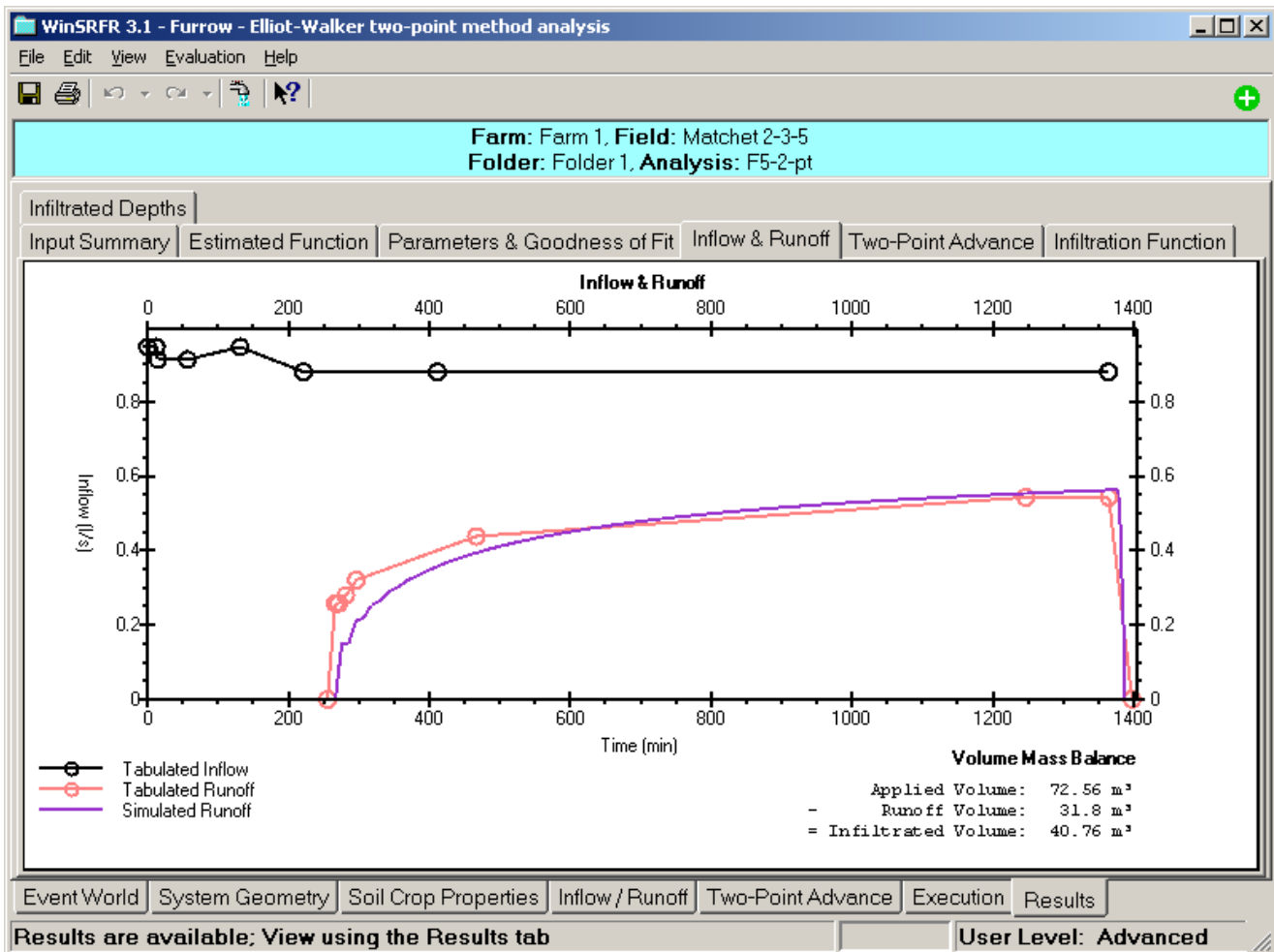
4.2.4 Erosion Parameter Estimation

Overview

THIS FEATURE HAS BEEN DISABLED FOR VERSION 3.1

Erosion simulation, available for Advanced Users of WinSRFR, enables calculation of furrow-soil detachment and entrainment into the furrow stream, transport downstream, and deposition at points of low flow velocity, in response to the simulated furrow flow and soil properties. Following the simulation, WinSRFR displays hydrographs of the calculated mass transport across sections located at the quarter and end points of the subject furrow. The post-irrigation net soil loss upstream from each quarter point and in the runoff is presented in metric Tons per hectare on the output page together with the hydraulic performance parameters for the simulated irrigation.

In the event that field data on soil erodibility is not available, WinSRFR can suggest a value based on a single measurement of sediment concentration (grams per liter) in a test-furrow flow at the quarter point of the furrow at a user-specified representative time. This information is entered in the Event Analysis World, in a data-input screen similar to the one in the Simulation World, except that the field erodibility parameters are left "to be determined," and data slots are made available for the measured concentration data. When the analysis is completed, the resultant values of erodibility and critical shear appear in the appropriate windows. The information can be used for subsequent simulation studies by copying the data from the event folder (in the Project Management window) and pasting into a simulation folder.

Sediment components: the mix of grain sizes prevalent in the furrow soil is entered in the table in terms of the fraction of the mix coarser than a given size. Commonly, the mix is specified as percentages of sand, silt, and clay. The larger sizes are retained on sieves with a given size of perforations, e.g., sand can be considered to consist of particles that will not pass through 50 micron openings, i.e., are retained; silts pass through a 50 micron sieve, but are coarser than 8 microns (the very small particle sizes are too small for mechanical sieving, and their fraction is determined by standard pipette techniques based on fall velocities and Stokes' Law). The fraction (100% - % sand - % silts) of the mix smaller than 8 microns can be considered clays. The components can be entered directly into the table or entered using the Sand / Silt / Clay Dialog Box.

If data are available, the specific gravity of the particles can be entered, replacing the default 2.65. **Water temperature** affects its viscosity and sediment fall velocity, and is entered in the pertinent dialogue box.

In performing either simulations or evaluations, WinSRFR utilizes a theoretical, continuous particle-size distribution based on the discrete sediment components entered in the table. In the input dialogue, the user can select a finer or coarser resolution in the theoretical distribution that is fitted to the entered size data -- with either a Gauss normal, or piece-wise linear (recommended) fit.

4.2.4.1 Inputs

Erosion Tab - for Erosion Parameter Estimation provides four input sections:

- Sediment Components
- Particle Size Distribution
- Irrigation Water
- Erosion Measurements

and one output section:

- Soil Erodibility (calculated)

Prior to estimating the Soil Erodibility parameters or running an erosion simulation, the Sediment Components that make up the field's soil must be entered. The components can be entered directly into the table or entered using the Sand / Silt / Clay Dialog Box.

When estimating the Soil Erodibility parameters, a single field measurement must be made during an irrigation. The amount of soil in grams per liter that is contained by the irrigation water must be measured 1/4 of the distance down the field at a representative time during the irrigation.

4.2.4.2   Sand / Silt / Clay Sediment Components

Prior to running an erosion simulation, the Sediment Components of the field's soil must be specified. A common method to enter this data is to divide the soil into three components:

- **Sand** - particles larger than 50 microns
- **Silt** - particles larger than 8 microns and smaller than 50 microns
- **Clay** - particles smaller than 8 microns

Two sieves, one 50 microns and the other 8 microns, are required to determine the sand, silt and clay components.

1. Sieve a soil sample through the 50 micron sand sieve and enter the retained amount as the sand percentage.
2. Sieve the remaining soil through the 8 micron silt sieve and enter retained amount as the silt percentage.
3. The remaining soil is assumed to be clay and is calculated automatically. (100% - Sand % - Silt %)

If desired, the Specific Gravity of the sand and silt can be modified from their default 2.65 values.

4.3 Hydraulic Simulation

Overview

The Simulation World provides a one-dimensional mathematical model for simulating surface irrigation -- in borders, basins, and furrows. It is assumed that all flow characteristics vary only with distance from the inlet and time. No variation transverse to the main direction of flow is considered. Thus, any cross slope in borders and basins is assumed negligible; also, the inflow therein is assumed distributed uniformly across the width. Only single furrows are considered; neighboring furrows are assumed to have identical flows --any variation in properties from furrow to furrow within a field must be modeled separately. On the other hand, field properties like the infiltration characteristics and roughness, bottom slopes, and furrow cross sections for example, can have a prescribed variation with distance along the bed, and even with inundation time.

The results of a simulation, like those of an actual run in the field, depend on the hydraulic properties of the soil and crop (if the vegetation is immersed in the flow), the physical design of the system (length, slopes, etc.), and the irrigation management: flow rates, duration, etc., as well as the target depth of infiltration for the irrigation. When all of these quantities are prescribed by the user -- through the interactive data-entry windows -- the simulation can be performed. The results -- the advance and recession curves, the runoff, and the distribution of infiltration depths along the length of the run when recession is complete -- can be presented both graphically, and numerically through a series of performance indicators, such as application efficiency, distribution uniformity, adequacy of irrigation, water cost per application, etc. Moreover, the graphical results of several simulations under different conditions can be superimposed in different colors for convenient comparison. During the course of each simulation, an animated graphic of the soil and water surfaces, and the growing infiltration profile in the soil are displayed.

The simulations consist of numerical solutions of equations which represent, mathematically, universal physical principles like conservation of mass and momentum. These general equations are complemented by user-given conditions of the irrigation to make a specific solution possible.

Applicability

The Simulation World can be used to simulate the surface irrigation of furrows, borders, and basins. Several options are provided for specify the field geometry (cross section, length, width, bottom slope), hydraulic resistance characteristics, infiltration behavior, upstream boundary conditions (inflow rate and cutoff time), and downstream boundary conditions (open or closed).

4.3.1 Inputs

Simulation World Tab

The Simulation World Tab offers three sets of option buttons:

- Cross Section is used to select the irrigation system type, (furrows or borders/basin)
- Upstream Condition is used to disable/enable simulations with drainback flow
- Downstream Conditions is used to specify if the field is Open or Closed at the downstream end (i.e., systems with or without runoff).

Common Inputs

System Geometry tab

Input	Input / Output	Use
Length	Input	See section 4.1.1 System geometry. Required.
Width/Set Width	Input	See section 4.1.1 System geometry. Required.
Furrows per set	Input	See section 4.1.1 System geometry. Required, if simulating furrows.
Overflow/Maximum depth	Input	See section 4.1.1 System geometry. Simulation may fail if the computed depths exceed the specified overflow/maximum depth
Bottom Description	Input	See section 4.1.1 System geometry
Slope	Input	See section 4.1.1 System geometry

Soil / Crop Properties tab

Input	Input / Output	Use
Hydraulic Roughness	Input	See section 4.1.2 Soil/Crop Properties. Required.
Enable Vegetative Density	Input	See section 4.1.2 Soil/Crop Properties. Advanced option, not required for standard simulations
Infiltration Function	Input	See section 4.1.2 Soil/Crop Properties . Required.
Wetted Perimeter	Input	See section 4.1.2 Soil/Crop Properties. Required if simulating furrows.
Enable Limiting Depth	Input	See section 4.1.2 Soil/Crop Properties. Advanced option, not required for standard simulations

Inflow / Outflow tab

Variable	Input/ Output	Use
Unit Water Cost	Input	Not required
Required Depth	Input	Not required for simulation but needed to calculate the post-irrigation performance indicators. Performance indicators such as Application Efficiency are calculated relative to the specified target infiltration depth.
Inflow Method	Input	See section 4.1.3 Inflow Management. Required.
Inflow Rate	Input	See section 4.1.3 Inflow Management. Required.
Cutoff Options	Input	See section 4.1.3 Inflow Management. Required.
Cutoff Time	Input	See section 4.1.3 Inflow Management. Required.
Cutback Options	Input	See section 4.1.3 Inflow Management. Required.

Data Summary Tab

The Data Summary tab summarizes the data input from the three Common Data tabs: System Geometry, Soil / Crop Properties and Inflow Management. The Data Summary tab can be used to edit input values but not input options. For example, if the Kostiakov function is used to specify infiltration properties, then the parameters of that function can be edited, but you cannot change to a different infiltration formulation. To change selections or edit tabular data use the appropriate Common Data tab.

4.3.2   Execution

Execution Tab displays four sets of inputs:

- Solution Model
- Standard Criteria
- Advanced Criteria
- Run Control
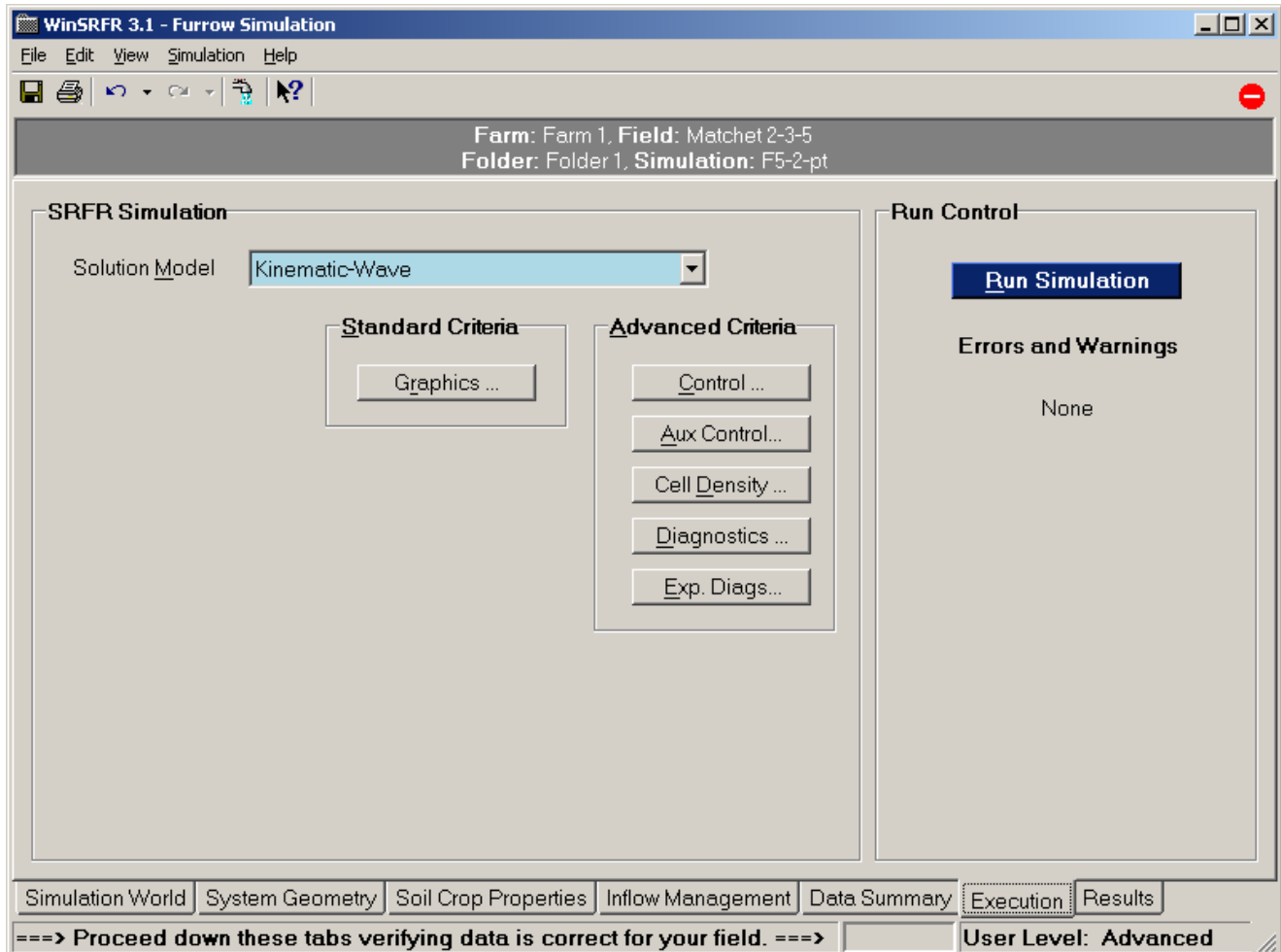
Two solution models are used by WinSRFR, the zero-inertia and the kinematic-wave models. The zero-inertia solution method is a simplification of the hydrodynamic equations of one-dimensional, unsteady, open-channel flow. Specifically, it deletes the acceleration terms to provide a more robust simulation. This is tantamount to assuming that the forces stemming from depth variations with distance, bottom slope, and hydraulic drag are in equilibrium. It is accurate under flow conditions with low Froude numbers, typical of irrigation, but is prone to some computational difficulties with steep slopes. The kinematic-wave model avoids these problems by assuming a normal depth relationship between depth and flow rate everywhere, but it is only applicable only when the slope is relatively steep and with open-ended systems. For steep slopes, the contribution of the depth gradient to the force balance is very small and can be neglected, leaving equilibrium between the force of gravity downslope and the hydraulic drag upslope which is the basic premise of the normal-depth assumption. WinSRFR switches the solution model from Zero-Inertia to Kinematic-Wave when the bottom slope exceeds

0.004, but only for open-ended systems. This selection is done for both the Standard or Advanced User. The Advanced user can override this selection, but the simulation will fail if the user selection is inapplicable under the specified field conditions.

The Standard Criteria/Graphics button is used to edit some graphical output options. Pressing the button brings up the Simulation Graphics Dialog Box, which contains two editable tables:

- 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 a flow rate/depth hydrograph data.

By default, WinSRFR selects five equally spaced locations at which to hydrographs and three times for profile capture. A maximum of 10 values can be entered in these tables. The hydrograph location table always includes the upstream and downstream field boundaries.

NOTE: In open-ended systems, the zero-inertia model computes zero depth at the downstream boundary after water reaches the end of the field. For those cases, WinSRFR will appear to display one less depth hydrograph than requested in the hydrograph location table.

4.3.2.1   Standard Simulation Criteria

The **Simulation Graphics** Dialog Box is available to all WinSRFR Users to select specific times and locations to capture data regarding the surface water as it flows down the field during a Simulation run.
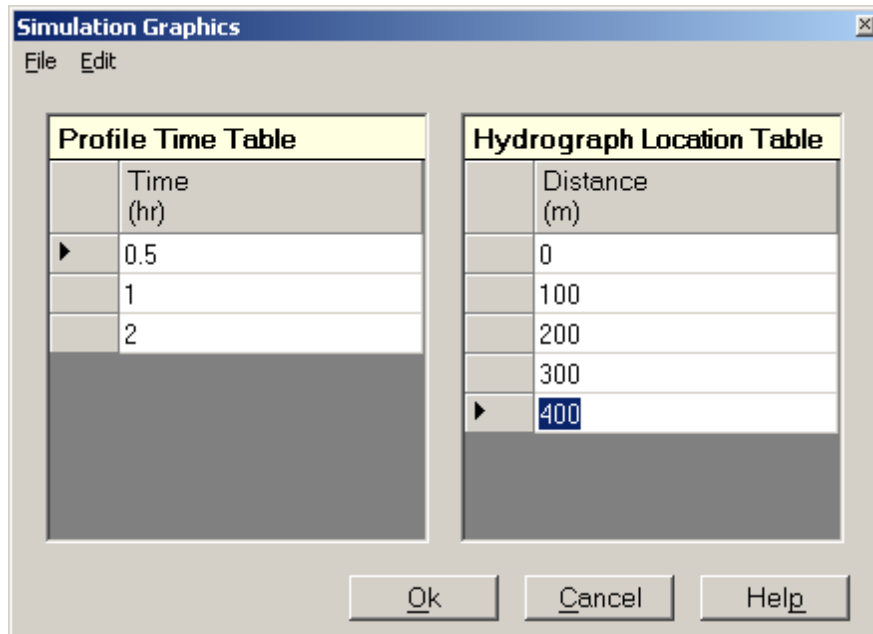
- The **Profile Time Table** specifies the <u>times</u> to capture and display a <u>depth profile</u> of the surface water as it moves down the field.

- The **Hydrograph Location Table** specifies the <u>locations</u> to capture and display a <u>flow rate hydrograph</u> of the surface water as it moves down the field.
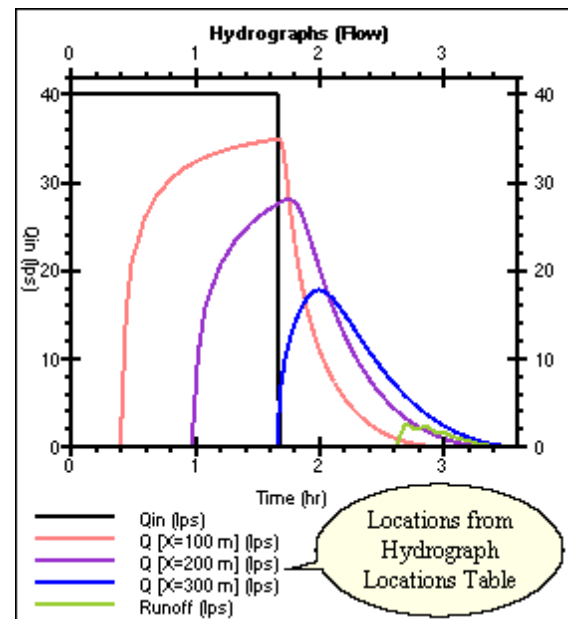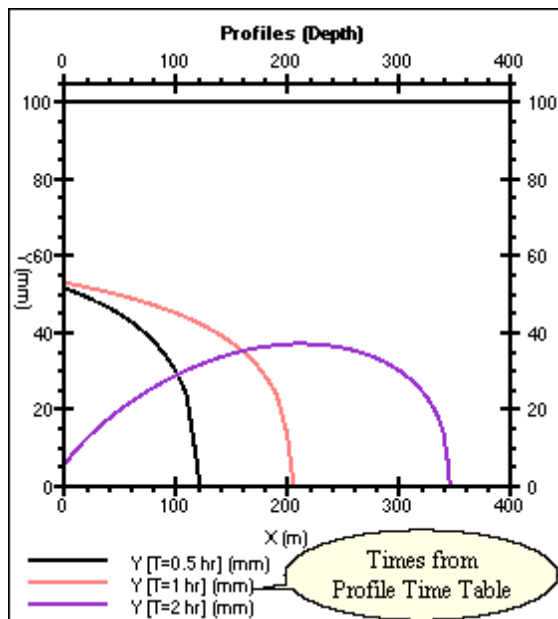
4.3.2.2   Advanced Simulation Criteria

The **Advanced Simulation Criteria** are available to the Advanced User only and are specified using several dialog boxes.

Cell Density

For Standard users, Cell Density is set by WinSRFR to best match the field conditions being simulated
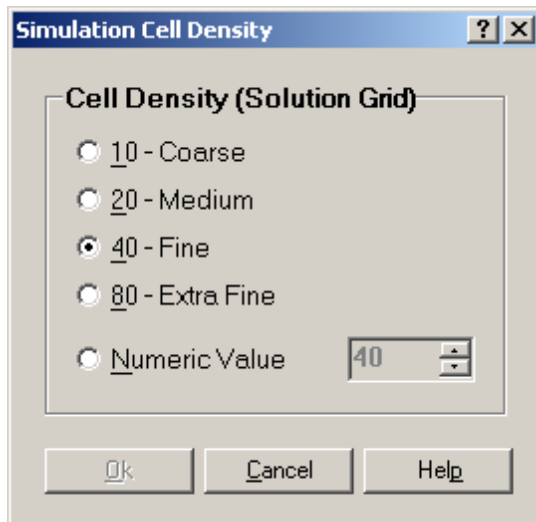
Cell density influences the number of cells into which the stream is divided for the numerical simulation. Furthermore, the smaller the cell size, the smaller is the initial time step. The time step typically grows with time, depending on the behavior of the simulation, while the cell sizes are fixed with time.

A coarse grid selects 1/10 of the length of run for the initial cell size; medium, 1/20; fine (a typical default), 1/40; and extra fine, 1/80. Smaller cells are accommodated by entry of numbers greater than 80, following selection of Numerical Value.

Other Advanced Criteria

The SRFR simulation engine offers a wide-array of diagnostic and control options that should only be used if those options are thoroughly understood.

- Diagnostics Options
- Control Criteria
- Auxiliary Control Criteria
- Experimental Diagnostic Criteria

4.3.3 Outputs

Results Tab displays the results tab with descriptions for these outputs . For mathematical descriptions of these outputs, see the Terminology section, in Technical Background.

Summary of output tabs

Tab	Type	Description
Summary	Table	Summary of inputs and computed performance measures
Hydraulic Summary	Graph	Combined graph displaying the inflow/outflow hydrographs, advance/recession trajectories, and the final infiltration profile.
Advance/Recession	Graph	Advance and recession as a function of time. The Advance tab displays advance data alone.
Infiltration	Graph	Depth of infiltrated water as a function of distance. The infiltration (Ordered) tab arranges these values in descending order
Upstream infiltration	Graph	Plot of infiltration depth as a function of time, computed from the simulation results. For borders/basins, it is calculated as the infiltrated volume per unit length divided by the border width. Therefore, it will be equal to the specified infiltration function. For furrows, it is calculated as the infiltrated volume per unit length divided by furrow spacing. It will be equal to the specified infiltration function only when using the furrow spacing as the nominal wetted perimeter option.
Hydrographs (Flow & Depths)	Graph	Flow rate/depth as a function of time at specified hydrograph locations
(Depth/Elevation) Profiles	Contour graph	Water surface depth/elevations as a function of distance computed at the times specified in the profile times table.

Viewing the Animation Window

After successfully completing a simulation, you can view an animation of the flow using the Water Flow Animation tool via the Simulation/View Simulation Animation Window menu item. The tool has controls that you can use to replay the simulation and save the output, frame by frame or as a complete simulation.

The screen is broken into two regions. The upper portion shows the irrigation stream, with its surface above the bottom of the flow channel a distance equal to the actual depth. The lower portion of the split screen displays the infiltration profile, drawn at a distance equal to volume infiltrated per unit field area. Thus the significance of the depth scales above and below the channel bottom is not exactly the same.
Shown on the animation frames (and influencing the vertical scale) are the top of the furrow (or top of border or basin berms). During periods of overflow (accounted for in furrow simulations with the physical assumption that neighboring furrows on either side have identical flows; not accounted for in border or basin simulations), a message appears on the screen, near the point of overflow.

The top of the furrow (field soil surface) or berms is assumed fixed with time, as the flow-channel bottom changes with assumed erosion or deposition. Also shown is the target depth of infiltration. The default vertical scale is influenced by this amount, and by the total expected depth of infiltration.

4.3.3.1 Simulation Results

After successfully completing an analysis, WinSRFR will display the corresponding results in a series of tabs located at the **top** of the window. These tabs are only visible after the Results Tab at the bottom of the window is selected. Results tabs display either text alone or a combination of text and graphs, with each tab representing a separate print page. Use the View menu to select the format for viewing & printing the results. Results will be displayed in the Results Tabs as long as the associated inputs do not change. If any inputs change , the results will be incompatible with the current input values and WinSRFR will alert the user with a message in the Results Tab. If accidental changes are made to the inputs, or if changes are made but then you decide to keep the original inputs and results, you can undo the input changes using the Edit/Undo commands. The output Result Tabs will display again when all original inputs are restored using the Undo commands.
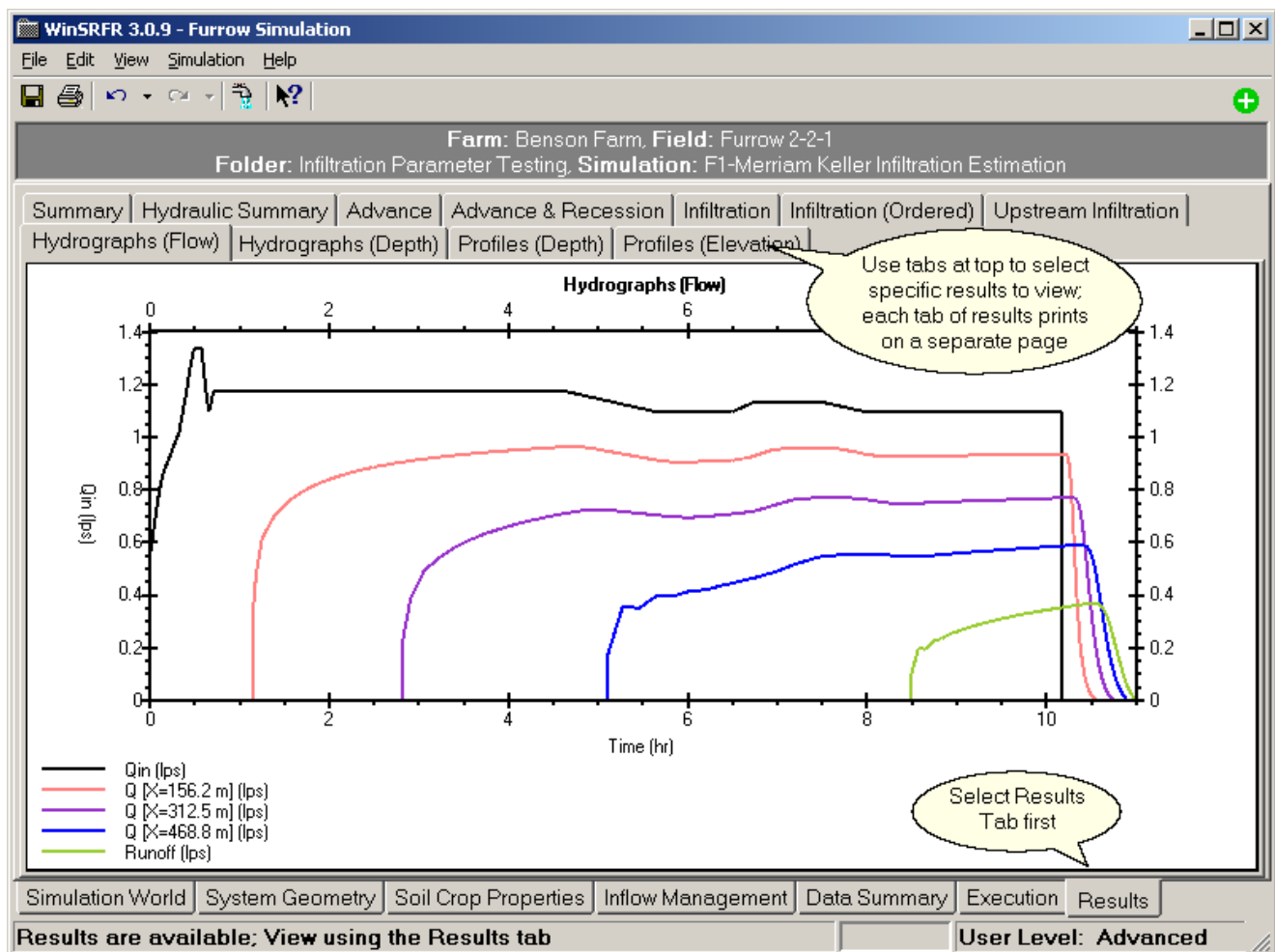
All graphs in the results tab can be copied to the clipboard as either a bitmap or data for pasting into application such as Excel or Word. Use either the right-click context menu or the Edit menu to access the Copy functions.

4.3.3.2 Irrigation Summary

The first Results tab is the Summary tab that displays pertinent input parameters and the calculated performance indicators:

Input Parameters

- System Geometry summary
- Soil / Crop Properties summary
- Inflow Management summary

Calculated Performance Indicators

- Hydraulic summary
- Efficiency & Uniformity Indicators
- Costs

4.3.3.3 Hydraulic Summary

The **Hydraulic Summary** graph is a combination of several sub-graphs that visually represent the major components on an irrigation: Inflow, Advance, Recession, Runoff and Infiltration as shown in the example below.
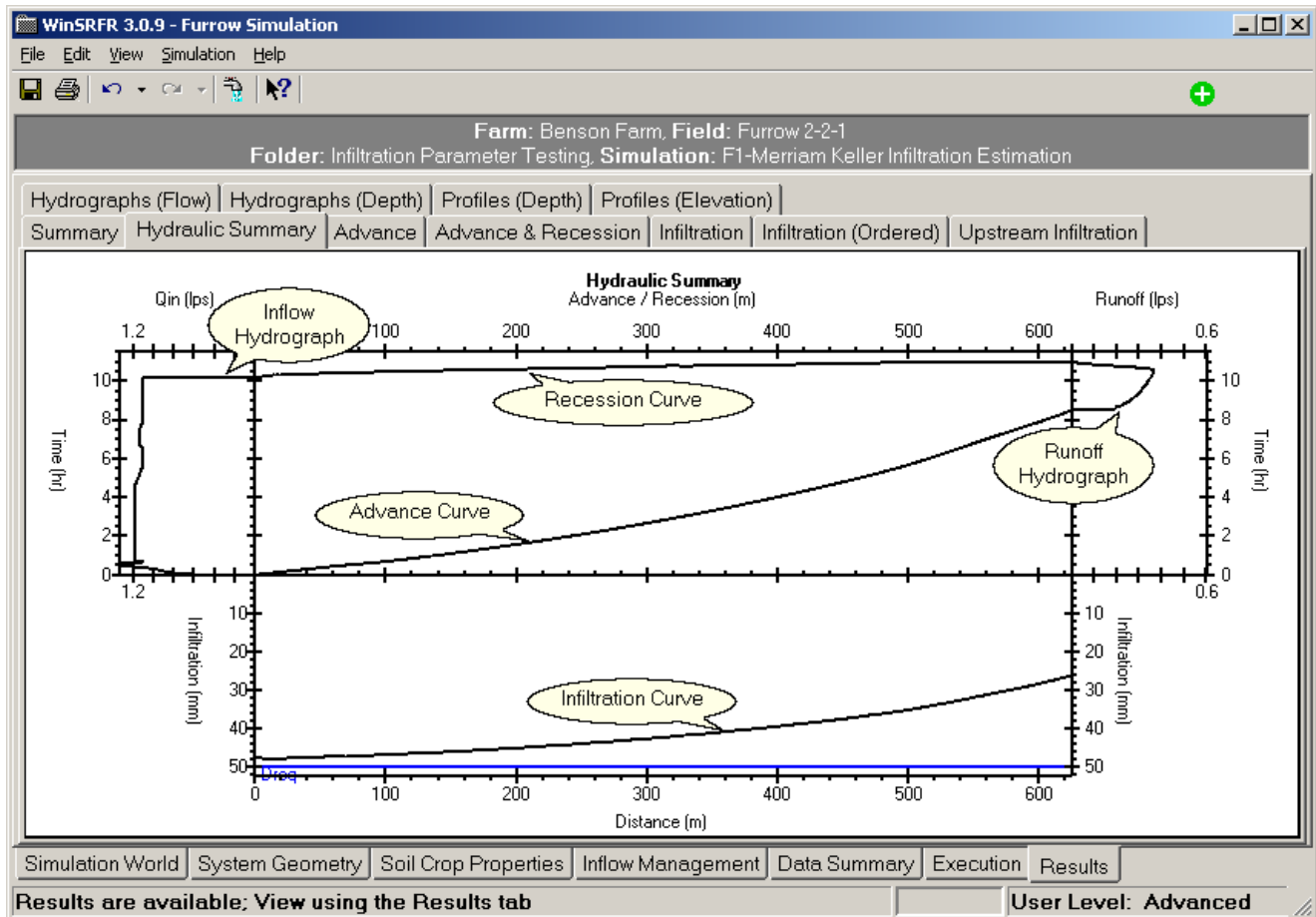
The Design World and the Operations World use the Hydraulic Summary to show a comparison between their computations and the SRFR Simulation of the same irrigation.

4.3.4   Examples

The **SRFR Examples.srfr** file contains examples originally installed with SRFR 4.06. These examples illustrate the use of a various system geometry and inflow configuration options provided by the software.

- **BORDER.DAT** Folder: Examples demonstrate options for specifying a distance-based cutoff, i.e., it forces the simulation to stop the inflow when the advancing stream reaches a specified distance from the field inlet.
  - Classical Criddle ¾ Rule - Specifies a distance-based cutoff 3/4 of the way down the field.
  - Distance-Based Cutoff at end the field - Triggers cutoff when the water reaches the end of the field.
  - Predict lag time, to achieve target at upstream end - Attempts to satisfy the irrigation requirement at the upstream end. To account for the lag time between cutoff and final recession, the target upstream infiltration depth is set at 95% of the requirement, Dreq.
  - Furrows within Border - Similar to the "Classic Criddle 3/4 Rule" example, but using furrows.

- **CUTBACK.DAT** Folder: Example shows use of distance-based reduction in inflow (cutback irrigation).
  - Example from National Engineering Handbook - Uses Time-Based Cutoff with Distance-Based Cutback.

- **DRAINBAK.DAT** Folder: Examples demonstrate drainback irrigation systems. The user specifies a drawdown time, following cutoff, that is an estimate of the time required for the excess surface storage to fully drain from the field. Individual examples combine the drainback option with a particular cutoff options.
  - Drainback level basin. Cutoff at 100% of basin length - Drainback at upstream end of field with Cutoff when Advance reaches end of the field.
  - Drainback level basin. 18cfs. Cutoff at 90% of basin length - Increases Inflow Rate while decreasing Cutoff location.
  - Compare with NO drainback - Removes Drainback from the previous example.

- **DUNKLIN.DAT** Folder: Example illustrates the use of the Enable Limiting Depth option for Infiltration. The limiting depth is an infiltration depth, not a soil depth. Thus, the assumption is that the user knows how many inches or millimeters of water will infiltrate before infiltration ceases due to the hardpan effect.
  - Hardpan Limits Infiltration - Effect of hardpan using Enable Limiting Depth option for Infiltration.

- **EGYLVL.DAT** Folder: Examples show how to configure the field bottom based on field elevations as a function of distance instead of using a single constant slope value. The examples also illustrate the effect of field bottom non-uniformity on irrigation performance.
  - Bottom config - Theoretical dead level – Constant slope (level furrow) for comparison.
  - After laser leveling - Elevation Table describes the furrow bottom after laser leveling.
  - After traditional land leveling - Elevation Table describes the furrow bottom after traditional land leveling.

- **FILTER.DAT** Folder: Examples are based on a filter strip design problem. The main feature illustrated is the use of a tabulated hydrograph to specify the field inflow. The main objective was to determine if the inflow would be contained within the filter strip under uncertain infiltration conditions.
  - Gary Conaway file - Border with a steep slope using Tabulated Inflow.
  - Same, with 1.5 NRCS Family - Same field with different NRCS Intake family defining Infiltration.
  - And now, with 0.20 NRCS Family - Same field with yet another NRCS Intake family defining Infiltration.

- **OVERFLOW.DAT** Folder: Examples shows handling of overflow conditions (water depth exceeding the furrow/border height)
  - ○ Izadi Test 1 - No overflow for comparison.
  - ○ Same with 118mm furrow depth; overflows - Shallow furrow that overflows down the field.
  - ○ Same with 108mm furrow depth; overflows upstream - Shallow furrow that overflows near the upstream end of field.
  - ○ Overflowing borders - Border that overflows.

- **TOMSHOPS.DAT** Folder: Examples are for a field with an extreme slope. Such slopes can cause computational problems.
  - ○ Tom's hops. 660 ft run on 7% slope. - Long steep furrow irrigation.
  - ○ Test case of Tom's - Cuts field length by 1/2.

- **TWIN.DAT** Folder: Examples combine distance and Infiltration Depth cutoff options with a bottom configuration based on a slope versus distance table.
  - ○ Cutoff when target infiltrated at furrow end - Distance & Infiltration Depth cutoff.
  - ○ Example 1 with broken bottom. Same average - Adds Slope Table for uneven slope with two slope segments.
  - ○ Example 1 w/ broken bottom. Slope decrease then increase - Adds Slope Table for uneven slope with three slope segments.
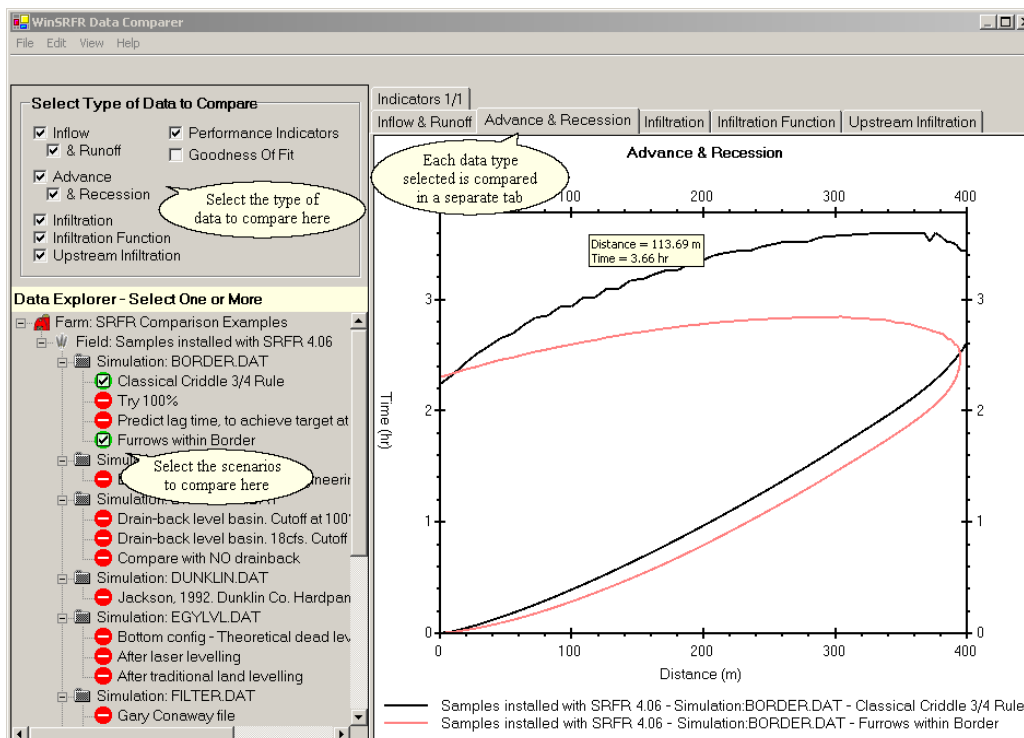
The Data Comparison tool can be used to compare results from multiple simulations within each example folder.

Besides comparing results from two or more simulations, this tool can compare results from other WinSRFR Worlds as well. Results from the Design World can be compared to several validation simulations perhaps.

4.4 Design Analysis

Overview

Design of surface irrigation systems aims to define a system length and width, that will result in a high level of performance (application efficiency and distribution uniformity) and satisfy the irrigation requirement everywhere (minimum infiltrated depth Dmin equal to the required application depth Dreq) for given a set of field conditions. Those conditions include the geometrical characteristics (slope, and cross section), infiltration and roughness properties, target application depth, and available inflow rate. For a given flow rate, different combinations of field length and width will require different values of cutoff time and will result in different levels of performance. Numerous unsteady flow solutions are needed to properly identify one or more designs that will satisfy the problem's requirements and meet additional practical constraints.

The Physical Design World is used to analyze system design. The analysis relies on performance contours as a function of the decision variables. These performance contour graphs are analogous to topographical maps, which display the variation in field elevation as a function of distance coordinates (X, Y). With the performance contour maps, you can visualize the effect of increasing length and width on performance and identify one or more solutions that will result in high efficiency and uniformity, meet the irrigation requirement, and also satisfy practical constraints. Contours are displayed for the following performance measures:

- Potential application efficiency
- Distribution uniformity
- Applied depth
- Deep percolation (depth)
- Low quarter infiltrated depth
- Cutoff Time
- Advance Ratio

The contours are generated using volume balance calculations calibrated by zero-inertia simulation results. Consequently, performance results extracted from the contours are approximations to predictions obtained with unsteady flow simulation. Details on these computational procedures are provided in the Technical Reference section of this manual and in several technical publications[1].

See Surface Irrigation Design for more information.

Applicability

The Physical Design World can be used to analyze furrows, borders, and basins, either with an open or closed downstream end. Procedures apply to graded or level systems, but calculations assume a uniform field slope. The analysis can be conducted assuming a constant inflow rate or a flow cutback strategy (furrows only).

_____

[1] Clemmens, A. J., E. Camacho, and T. S. Strelkoff. 1998. Furrow irrigation design with simulation. p. 1135-1140. _In_ Int. Conf. on Water Resources Engineering Proceedings, Memphis, TN. Aug. 3-7, 1998.

Clemmens, A. J. 2007. Simple approach to surface irrigation design: Theory. _e-Journal of Land and Water_ (1):1-19.

Clemmens, A. J. 2007. Simple approach to surface irrigation design: Spreadsheet applications. _e-Journal of Land and Water_ (1):20-43.

Strelkoff, T. S. and A. J. Clemmens. 2007. Chapter 13. Hydraulics of surface systems. 13:437-498. G. Hoffman, R. G. Evans M. E. Jensen D. L. Martin R. L. Elliott (ed.) _In Design and Operation of Farm Irrigation Systems, 2nd Edition._

4.4.1   Furrow Design

This example, as well as the following Basin / Border Design, are based on examples from:

Clemmens, A.J. 2007. **"Simple approach to surface irrigation design: Theory"**
eJournal of Land and Water, Vol. 1, 1-19

Clemmens, A.J. 2007. **"Simple approach to surface irrigation design: Spreadsheet applications"**
eJournal of Land and Water, Vol. 1, 20-43

Both papers and their accompanying Excel spreadsheet applications can be found at:

http://www.sakia.org/ejlw_2007_01_01_i
http://www.sakia.org/ejlw_2007_01_02_i

This example is based on section 5.2 Sloping Furrows and the Excel spreadsheet:

ejlw_2007_01_02_clemmens_furrow_design.xls

4.4.1.1 Inputs

Design World Tab

In addition to selecting the irrigation system type, (furrows or borders/basin) and the downstream boundary condition, the Design World Tab is used to select the decision variables that will be used in the analysis. This is done by selecting one of the two available Design Contour options.

Typically, the user will want to <u>Examine the Tradeoffs in Performance as a Function of Length and Width for a Given Inflow Rate</u>. Such an approach is used when the inflow is fixed or when the design wants to always take advantage of the maximum available flow rate.

An alternative approach is to <u>Examine the Tradeoffs in Performance as a Function of Length and Inflow Rate for a Given Width</u> (or furrow set width). This approach is most useful when the width is set by land-grading operations or when examining design relationships on a per unit width basis (i.e., when examining relationships for an individual furrow or for a border/basin section 1 m (1 ft) wide).
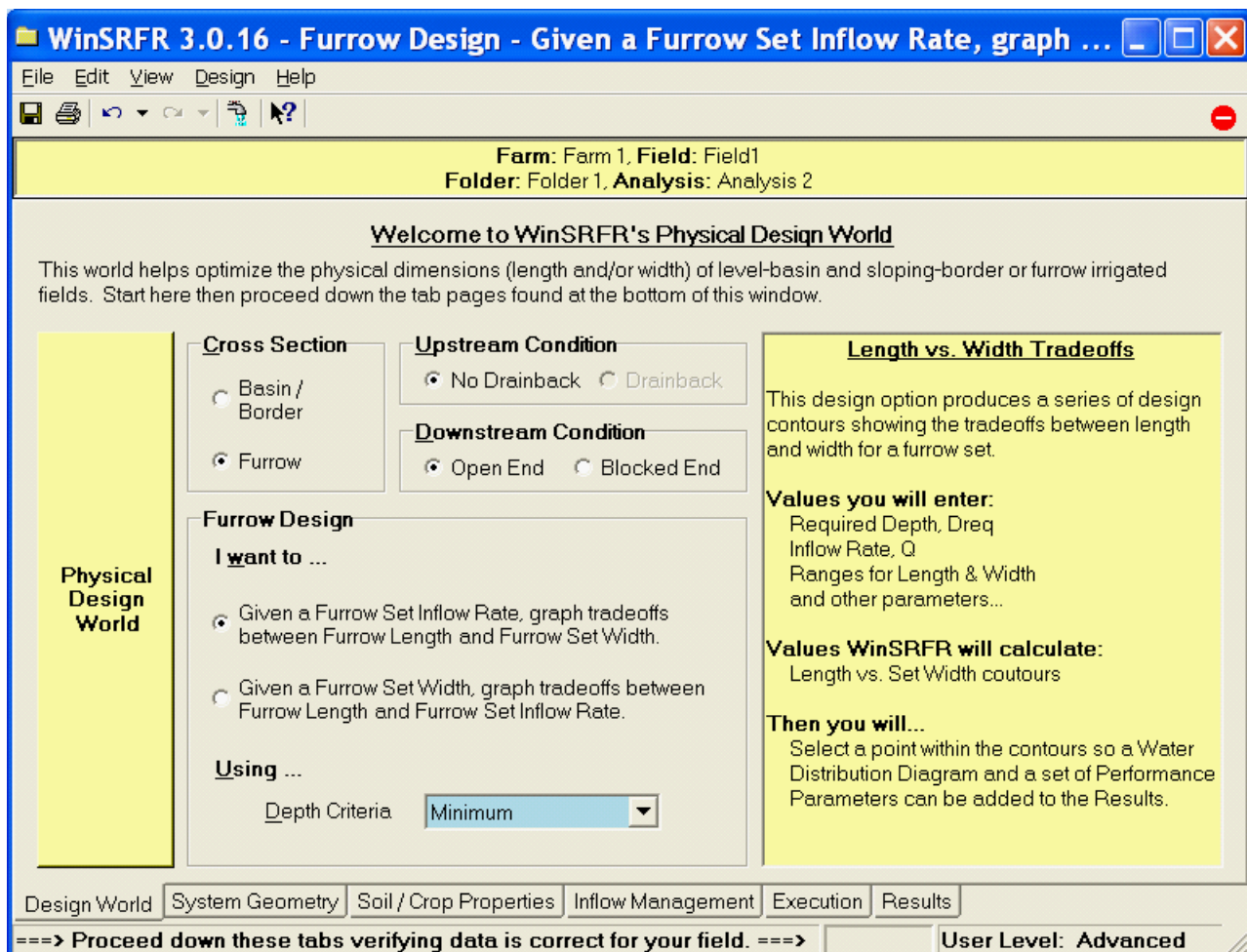
The Design World Tab also displays a control for Depth Criteria. At this time, this option is non-selectable as WinSRFR design procedures use only the Minimum Depth Criteria (i.e. solutions satisfy the condition Dmin = Dreq). Future versions of the program may add a low-quarter Depth Criteria (Dlq = Dreq) similar to the one used in the original BORDER program.

Common Inputs

System Geometry tab

Input	Input/Output	Use
Length	Output	The Length box will be disabled for input but will display the length for the selected solution point, after the analysis is run
Width/Set Width	Input or Output	The Width input box will be disabled if the Design Contour option is to plot Length and Width for a given inflow rate. The box will display the width for the selected solution point. The box will be enabled if the selected Design contour option is to plot length vs. inflow rate for a given width
Maximum depth	Input	Used indirectly, the simulation engine (which is used in calibration and when computing a solution point)
Slope	Input	Design analysis assumes a constant slope, which can be given as a single value, or calculated from a user-entered table of elevations (slopes) with distance

Soil / Crop Properties tab

Input	Input/Output	Use
Hydraulic Roughness	Input	Design analysis uses the Manning roughness option, either user-entered or selected from the table of NRCS recommended values
Infiltration	Input	With borders/basins, any infiltration formula used by WinSRFR's simulation engine can be selected. With furrows, design analyses uses restricts the infiltration function choice to Kostiakov, Modified Kostiakov, and Branch functions and the wetted perimeter options to furrow spacing.

Inflow/ Outflow tab

Variable	Input/Output	Use
Unit Water Cost	Input	Not used
Required Depth	Input	Solutions match the minimum infiltrated depth to the required depth, Dmin = Dreq
Inflow Method	Input	Only a standard hydrograph is available for design,
Inflow Rate	Input or Output	Specifies the constant inflow rate assumed for design, or the initial flow rate assuming cutback examining depth and width alternatives for a given inflow rate. Otherwise, the box displays the inflow rate associated with the selected solution point
Cutoff Options	Input	Analysis assumes time-based cutoff only
Cutoff Time	Output	Calculated value, text box will display the cutoff time of the selected solution point
Cutback Options	Input	With furrows, the design can be based on constant inflow or inflow with cutback

4.4.1.2 Execution

Execution Tab

The Execution Tab contains four sets of inputs, one of which is non-selectable by the user.

The **Design Parameters** section allows the user to modify the selection made in the Design Contours section of the Design World Tab and the irrigation target depth (Required Depth). If the (Furrow/Border/Basin) Inflow Rate option is selected, the program will generate Length vs. Width contours for a given inflow rate. The inflow rate can be modified in the corresponding input text box. If the (Furrow Set/Border) Width option is selected, the program will generate Length vs. Discharge contours for the given width, shown in the respective input box.

Contouring parameters are specified in the **Contour Definition** section. A key input is the range of the decision variables to be examined, Length vs. Width or Length vs. Inflow Rate. This is range is defined by minimum and maximum values. While the software may recommend a range of minimum and maximum values, the user may want to specify values based on practical constraints. For example, if the total field length and width are both 400 m, the analysts may want to enter 400 m as the maximum (border/furrow set) length and width. Development of a contour graph for a specific problem is in general a two step process. 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 reduced to develop a second contour graph, focusing on a particular region of interest, to improve the accuracy of results.

Three other inputs need to be specified in the Contour Definition section. One is the choice of grid size, selected with the Contour Grid Size drop-down control. WinSRFR calculates performance results at discrete points on a rectangular grid. Results from those discrete points are used to generate the contours. A finer grid will result in more accurate contours but will also increase the computational burden. A second choice is the type of contours, selected with the Standard and Precision Contour option buttons. This selection affects the computational procedures used for contouring. Precision Contours are potentially more accurate, but again are computationally intensive. The Show Minor Contours checkbox determines whether only major contours or both major and minor contours will be displayed in the contour graphs. For cases where contours are closely spaced, minor contours may make results difficult to read.
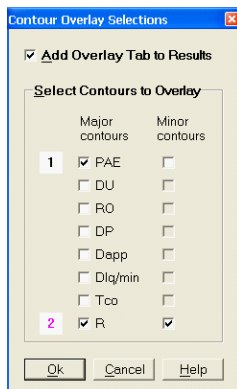
Finally, the **Add Contour Overlay** input button will bring up a new input form that is used to generate a contour overlay, in addition to the standard outputs. The relationship between two performance measures can be more easily examined when combining their respective performance contours.   Figure XX illustrates the Contour Overlay Selections form and the boxes that would have to be checked to generate a combined PAE-R overlay, with major and minor contours included for R. These particular outputs will be described later.

Calibration of the volume balance results are controlled by the inputs provided in the **Tuning Factors** section. The inputs are the value of the surface shape factor Sigma Y and the coordinates of the tuning point (length and width or length and inflow rate). The default value for the shape factor is 0.75 is adequate for most calculations. In general, the recommended approach is to place the tuning point at the longest length and midway through the width or inflow rate range. After editing these values, press the Estimate Tuning Factors button. WinSRFR will run through a series of unsteady flow simulations to complete the calibration process. If the tuning is successful, the program will display completion messages and the computed calibration parameters will be displayed in the boxes labeled Phi0-Phi3. Otherwise, the program will suggest an alternative location for the tuning point or ask the user to provide an alternative location. For those cases, the suggestion is to reduce the length coordinate first and then attempt a new calibration. If problems persist, then the option is to vary the location of the second coordinate value. NOTE: the tuning calculations are specific to the given set of inputs. While WinSRFR will allow to rerun the design without recalibrating, changes to any particular input invalidates the existing tuning results.

The **Run Control** identifies the simulation engine used for calibration, zero-inertia or kinematic wave. This choice is set by the program and is, therefore, disabled but displayed for informational purposes.

After completing the tuning process, press the Run Design button. The program will then compute the contours. Messages indicating the progress of the calculations will be displayed at the bottom of the Execution tab. If the calculations are successful, WinSRFR will display the computed contours. Some computational problems will cause WinSRFR to display warning/error messages. Those messages mostly relate to solution regions that do not satisfy the problem's requirements (e.g., that do not satisfy the condition Dmin=Dreq). Those messages are provided for informational purposes and can be closed to allow the program to display the contours.

Tuning Factor Usage

Design contours can be tuned to match the SRFR Simulator for the selected contour range using the **Tuning Factors** controls. Typically, the mid-point of the right edge of the contours is used as the tuning point but this point can be chosen anywhere within the contour range. After changing a Design Parameter, the Tuning Factors should be re-calculated using **Estimate Tuning Factors** prior to running the analysis. The tuning factors make the performance contour match at the calibration point, and the performance from simulation will vary as one moves away from the tuning point. For most cases, the deviations are small. However for shallow border strips with blocked ends, deviations tend to be larger. One can examine these errors by choosing solution point at various locations on the contour graph and choosing these as the solution point, which causes WinSRFR to run a simulation for comparison. If deviations are too large, the user can change the solution point to a location closer to the location of interest in the execution tab and rerun the entire contour plot. For level basins, the calibration point is changed if it is out of a reasonable range. Both the calibration point and the solution point are shown on the performance contour map.

The **Contour Grid Size** selects the density of the underlying grid of solutions used to generate the contours. The **Add Contour Overlay** button produces an additional Results tab showing an overlay of the selected contours. Press **Run Design** to generate the design contours that are viewed using the Results tab.

The **Tuning Factors** adjust the results computed by the design algorithms to match the results produced by the SRFR Simulator. They are used differently depending on the physical layout of the field. In general, Phi 0 matches the advance time to the end of the field, Phi 1 matches the downstream recession time, then the infiltrated volumes are matched using Phi 2 & 3.

Furrow Tuning Factors (Open or Blocked End)

- **Phi 0** - adjusts the advance time to the end of the field to match the SRFR Simulator
- **Phi 1** - adjusts the cutoff time (Tco) so the recession times at the end of the field match
- **Phi 2** - adjusts the recession at the head of the field so the infiltrated volumes match
- **Phi 3** - unused

Level Basin Tuning Factors (Blocked End)

- **Phi 0** - adjusts the advance time to the end of the field to match the SRFR Simulator
- **Phi 1** - adjusts the cutoff time (Tco) so the recession times at the end of the field match
- **Phi 2** - unused (the recession time at the head of the field is calculated so the infiltrated volumes match)
- **Phi 3** - unused

Sloping Border Tuning Factors (Open or Blocked End)

- **Phi 0** - adjusts the advance time to the end of the field to match the SRFR Simulator
- **Phi 1** - adjusts the cutoff time (Tco) so the recession times at the end of the field match
- **Phi 2** - adjusts the recession time at the head of the field to match the SRFR Simulator
- **Phi 3** - adjusts the slope of the recession curve to match the infiltrated volumes

The use of the Sloping Border Tuning Factors is illustrated in the following Hydraulic Summary graph that overlays the Design World's irrigation computations with the SRFR Simulation of the same irrigation. The Design results are shown in **black** while the Simulation results are shown in **salmon**.
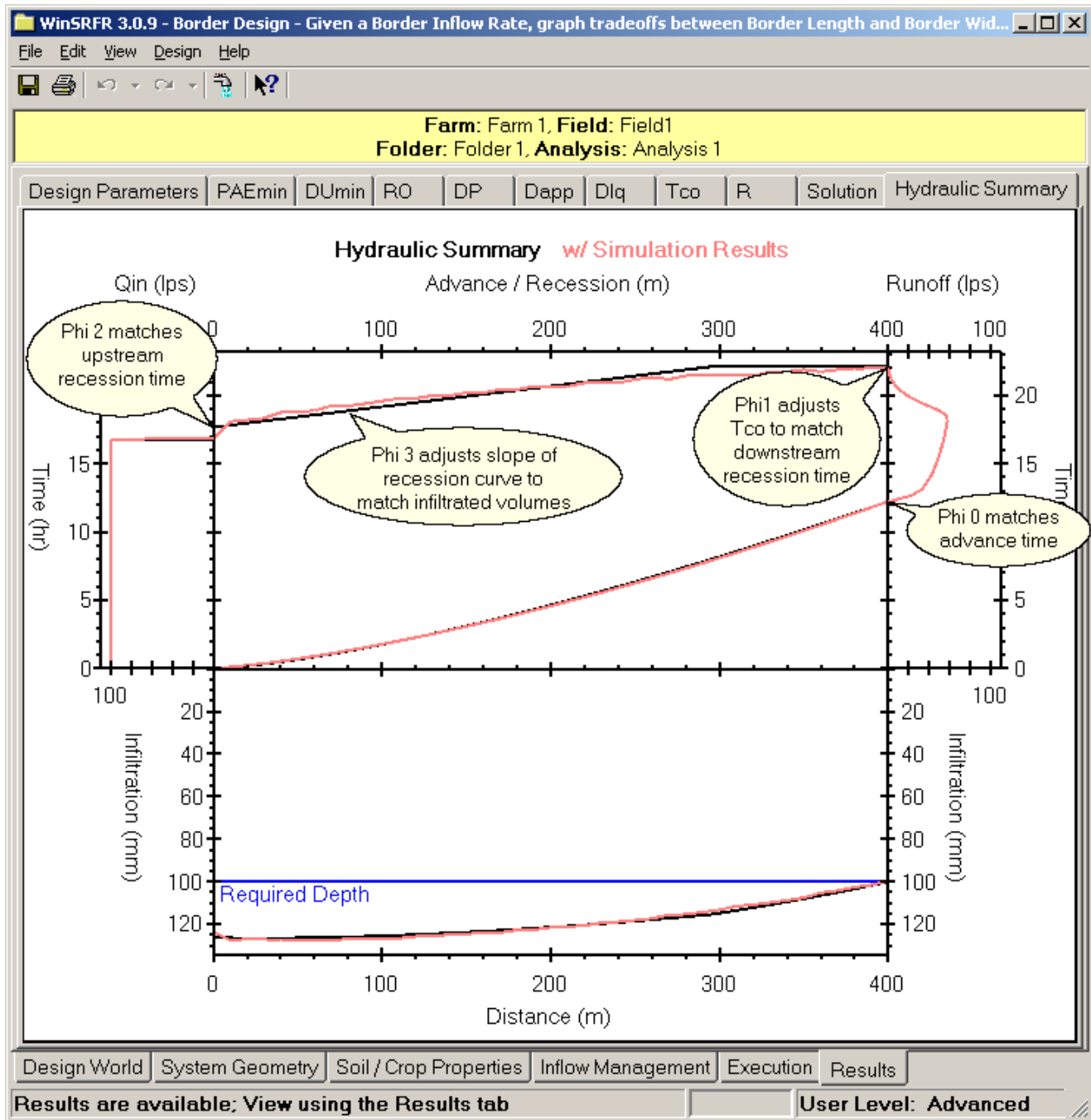
4.4.1.3 Outputs

The outputs of the design analysis, described in following table, are displayed by the results tab. For mathematical descriptions of these outputs, see the Terminology section, in Technical Background.

Summary of output tabs

Tab	Type	Description
Input Summary	Table	Summary of inputs
PAEmin	Contour graph	Potential Application of the minimum
DUmin	Contour graph	Distribution Uniformity of the Minimum
DP	Contour graph	Deep Percolation
Dapp	Contour graph	Applied Depth
Dlq	Contour graph	Low-quarter infiltrated depth
Tco	Contour graph	Cutoff Time
R	Contour graph	Advance Ratio = • Advance Distance at Cutoff Time/Length if R = 1, • Cutoff Time/Final Advance Distance Time if R>1
Solution	Graph	Infiltrated profile and performance summary for the selected solution point
Hydraulic Summary	Graph	Comparison of volume balance and unsteady flow simulation predictions for the selected solution point. Overlaid outputs include • Plot of advance/recession times with distance, • inflow and outflow with time, • plot of final infiltration depth with distance

Adjusting contour display options

WinSRFR offers various choices for displaying the performance contours. Those display options can be edited from the Edit/User Preferences command. More details are provided in Contours User Preferences.

Navigating the contours

The performance contours provide an overview of performance changes as a function of the decision variables. Additional details can be obtained by navigating over the contours with the cursor. WinSRFR will then replace the standard Windows arrow cursor with a cross-hair cursor and display the coordinates and of the point on the graph and its associated performance value.

For even greater detail, the user can launch WinSRFR's Water Distribution Diagram. This is done 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 any user-specified decision variable combination. The diagram can be forced to update dynamically while navigating over the contour region. To do this, move the Design Tab window to one side of the screen and the Water Distribution Diagram to the other side of the screen, so that the two windows do not overlap or overlap as little as 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 coordinate values can also be edited manually. If the selected point is of interest for further analysis, save it by pressing the Save as Solution button. Saving the solution point will copy the Water Distribution Diagram results into the Solution tab and will also update the Hydraulic Summary tab. The updated Hydraulic Summary Tab will display the advance and recession trajectories, infiltration profiles, and inflow and outflow hydrographs computed from volume balance calculations and from zero-inertia (or kinematic-wave) simulation. These results need to be compared in order to get a visual measure of the accuracy of the volume balance results in different regions of the contour graph. Volume balance and unsteady flow simulation results generally will be in close agreement throughout most of the contour region. In some regions, the two solutions will differ slightly in the computed advance and recession trajectories, in the breakdown between deep percolation and runoff losses, and in the shape of the infiltrated profile. However, they may still predict the same application efficiency. When analyzing a design problem for a very wide range of lengths/widths, volume balance calculations may differ significantly from the simulation results in part of the contour region. In those cases, the advance predicted with unsteady flow simulation will fail to reach the end of the field while the volume balance calculations will predict full advance and satisfaction of the Dmin=Dreq condition. Further analysis in this region requires a more detailed contour graph, based on a narrower range of lengths and widths (or flow rates).

Contours

The [Design World](#) makes extensive use of contours to show tradeoffs between solutions, depicted as black dots on the contours. A Solution Point, displayed on the Solution and Hydraulic Summary tabs, is chosen either using the right-click context menu within the contours or using View or Design menu items.
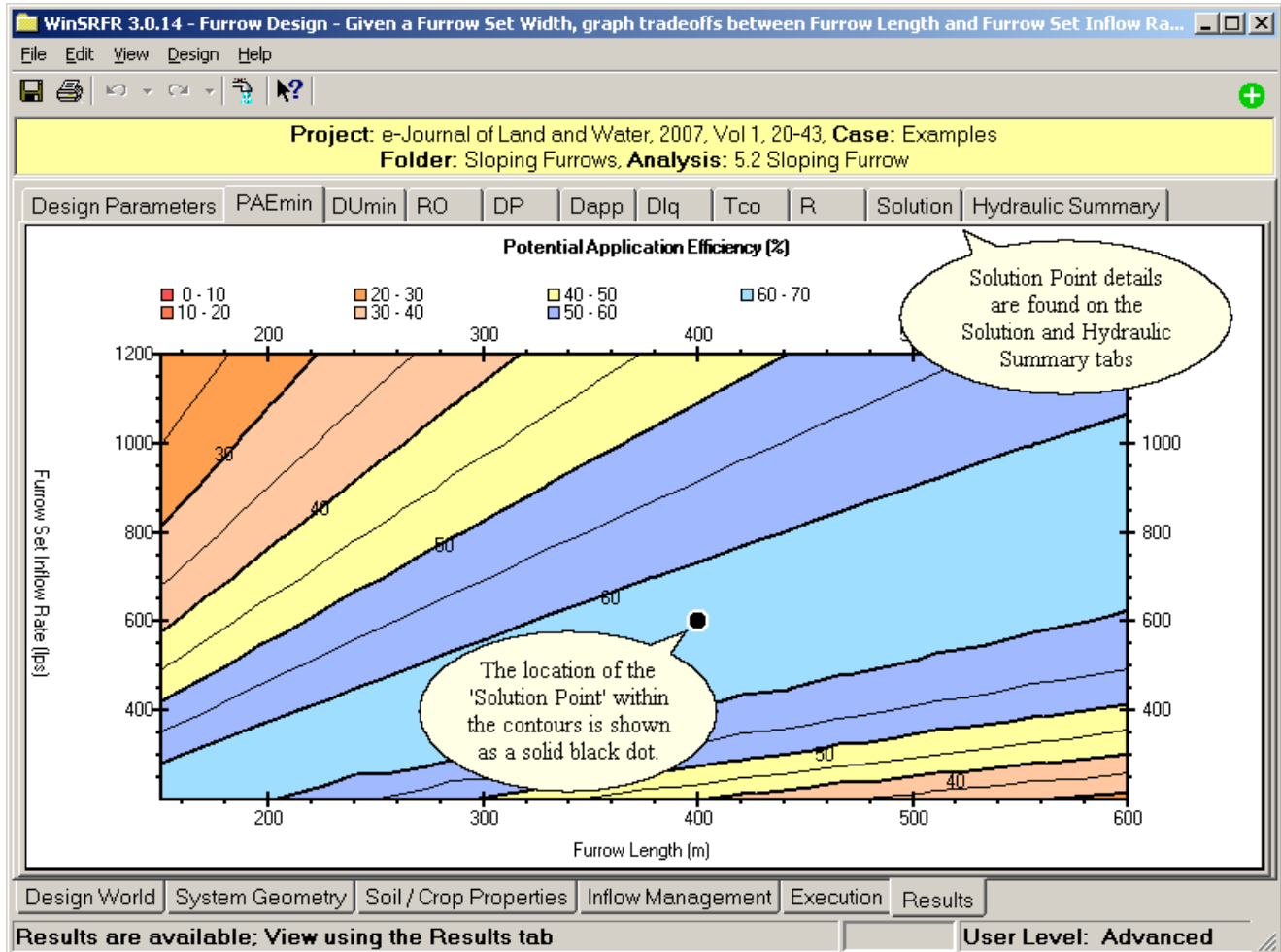
The Potential Application Efficiency (PAEmin) tradeoffs are shown for a range of Furrow Lengths and Furrow Set Inflow Rates; compare these contours with those found in the [spreadsheet example](#). You can see how PAEmin varies with the highest values in the middle of the contours and lower values toward the upper-left and lower-right corners. This is expected since the upper-left corner has higher inflow rates and shorter lengths resulting in high Runoff (see RO tab) while the lower-right corner has lower inflow rates and longer lengths resulting in high Deep Percolation (see DP tab). The tradeoffs for DUmin, RO, DP, Dapp, Dlq, Tco and R are shown on ensuing tabs.

Results from two or more contours can be overlayed for comparison purposes; use the **Add Contour Overlay...** button on the Execution tab to define what contours to overlay and view on the Overlay tab.

Contour Overlay

When working in the Design or Operations Worlds, users can add an Overlay Tab to the Results. The Overlay Tab combines the contour curves from the selected parameters.
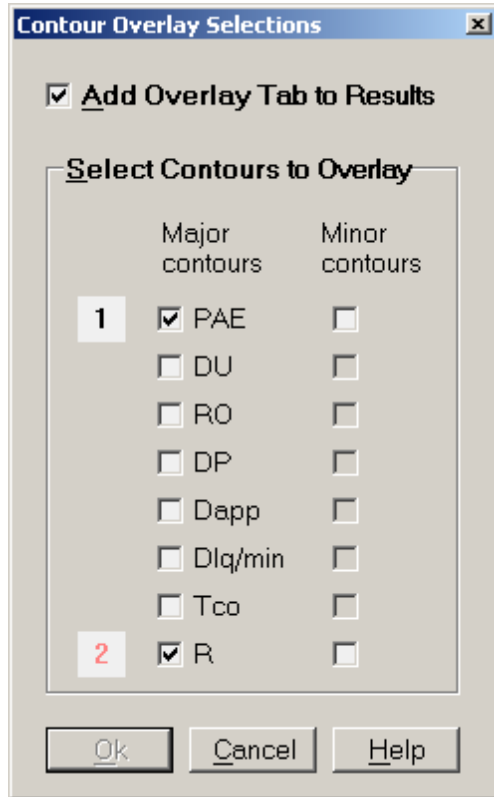
1. Use '**Add Overlay Tab to Results**' to enable or disable the Overlay Tab.

2. Select the **Major / Minor contours** to add to the overlay. The order of selection defines the color used to plot the curves; see the left column of numbers. Each number displays the color that will be used to draw that contour. The colors are chosen using the User Preferences Graphs tab.

The selections made in this dialog box resulted in the Contour Overlay shown below being added to the Results.

Solution Point

After a Solution Point is chosen from within the contours, an analysis is performed on that point and the results displayed using the Solution and Hydraulic Summary tabs.
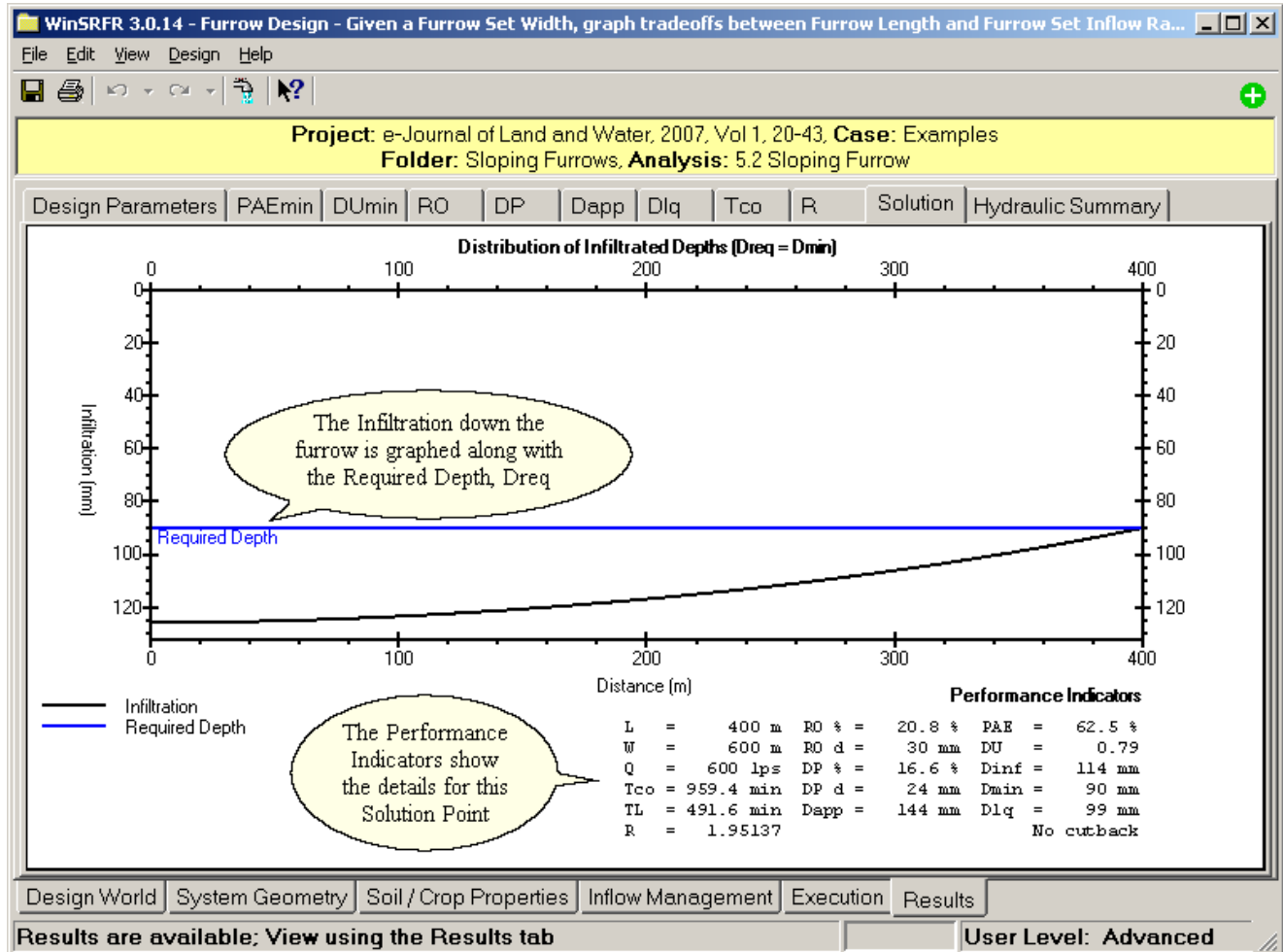
Hydraulic Summary

After a Solution Point is chosen from within the Contours, an analysis is performed on that point and the results displayed using the Solution and Hydraulic Summary tabs. The Hydraulic Summary is the Design World overlays a comparison of the quicker simple solution and the SRFR simulation of the Solution Point. For this example, the simple design results are drawn in black while the simulation results are in salmon.
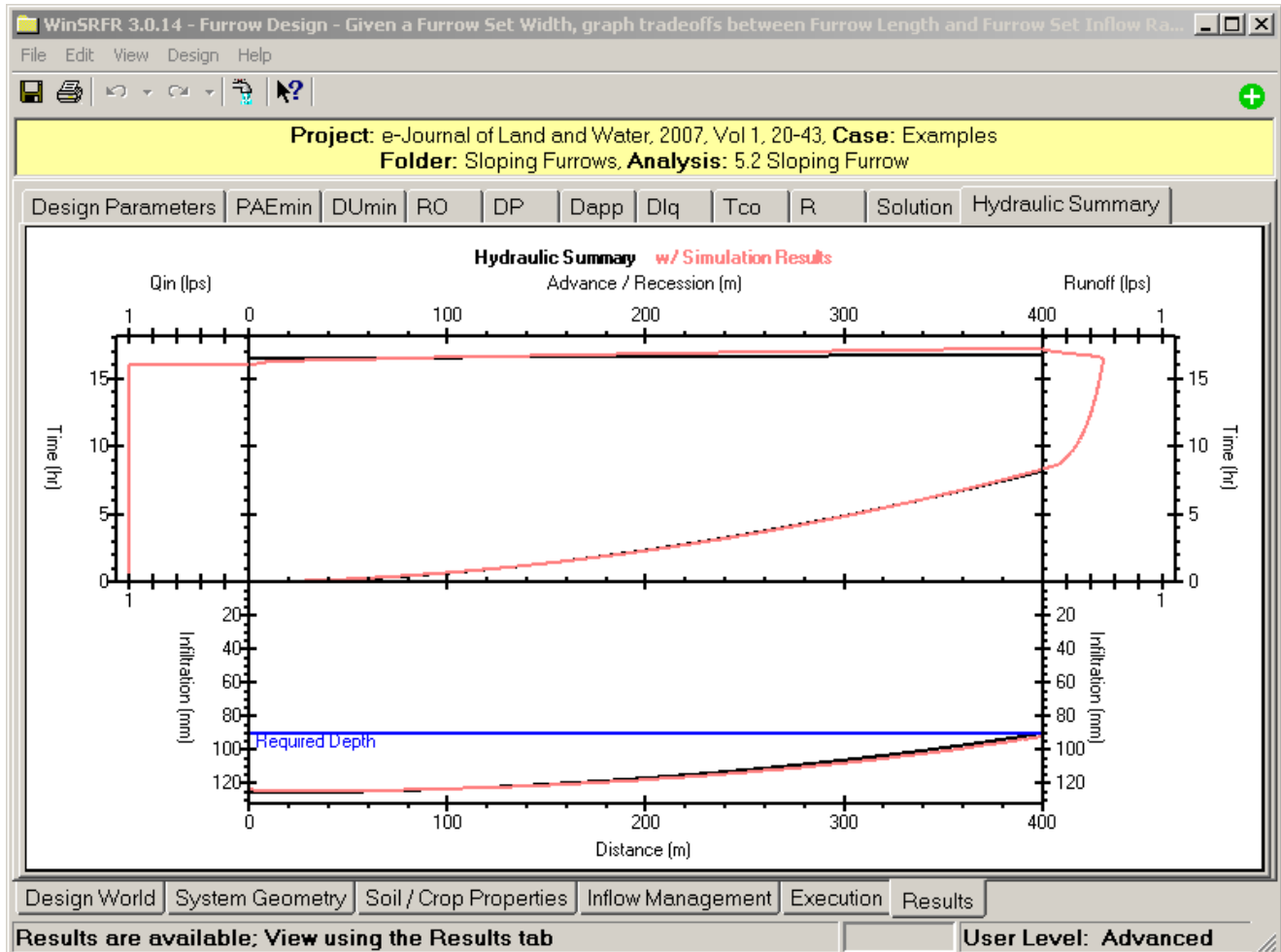
The design calculations and the simulation results match quite well but a close match would be produced had the design algorithms been 'tuned' to the simulation using the Tuning Factors found on the Execution tab. Remember that this example uses the default Tuning Factors so the results will match the spreadsheet example.

4.4.1.4   Examples

Design examples described herein are provided in the file e-Journal Examples.srfr. The file contains four folders, Sloping Furrows, Sloping Borders, Level Basins, and Level Furrows.

For all furrow examples, the given slope is 0.2%, the target application depth is 90 mm, and infiltration is given by the Kostiakov function with k = 30.1 mm/hr^a for furrows and k = 40.1 mm/hr^a for borders and a = 0.51 for both. A Manning n value of 0.04 is assumed for the furrow examples and of 0.15 for the border/basin cases. The furrow spacing is 1.0 m. It is important to note that the infiltration function given for these problems does not represent the same infiltration characteristics for furrows as for borders/basins. The furrow infiltration parameters incorporate the value of the furrow spacing specified for this problem and do not reflect the wetted perimeter through which water actually infiltrates.

The examples need to be run to view the results presented below. You may want to inspect the different inputs provided for each example before generating the contours. For each scenario, go to the Execution Tab and press the Estimate Tuning Factors button using the given tuning point and contour ranges. After the tuning calculations are complete, press the Run Design button. To view particular solution points, select them with the Water Distribution Diagram.

Sloping Furrows

The first scenario examines the performance tradeoffs with length and width for a given inflow rate, 283 l/s (10 cfs). The selected contouring range is 200-800 m (~ 1/8-1/2 mile) for length and 200-400 m ((~ 1/8-1/4 mile) for width. The calibration point was set at x = 600 m and y = 300 m (see the Execution Tab).
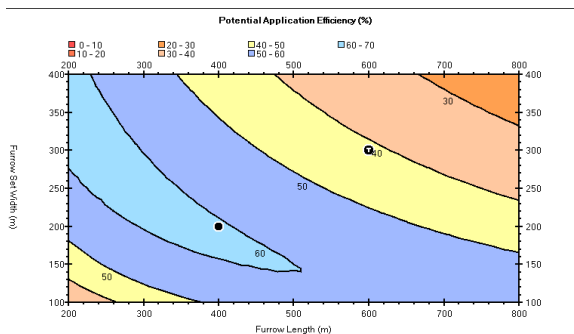
This is the PAEmin contour computed for this scenario. PAEmin is the maximum application efficiency that can be attained when the minimum infiltrated depth is equal to the irrigation requirement. The graph shows that a PAEmin of over 60% is attainable under the given conditions, but not for lengths over 500 m. As may be expected, fewer furrows are irrigated with the available flow as furrow length increases in order to achieve maximum performance. However, as length decreases, there is increasing flexibility in setting the field width for a PAEmin > 60%.

The graph shows two black circles. The one labeled with the letter T is the tuning point; the other is the selected solution point, 400 m length X 200 m furrow set width. The user is encouraged to inspect other contour plots generated for this example.
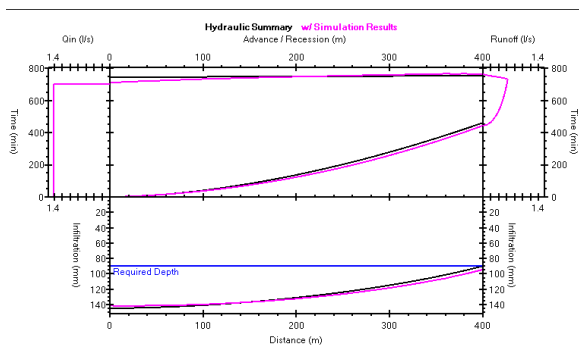
The hydraulic summary graph for the selected solution point contains two sets of curves. The black curves correspond to the results computed from volume balance, and the pink curves to the simulation results. For this example, the advance/recession and final infiltration profile curves are in reasonable agreement and suggest that the minimum infiltrated will exceed slightly the irrigation target with this design recommendation. The graph only includes a hydrograph computed with unsteady flow simulation, as one cannot be computed from volume balance.
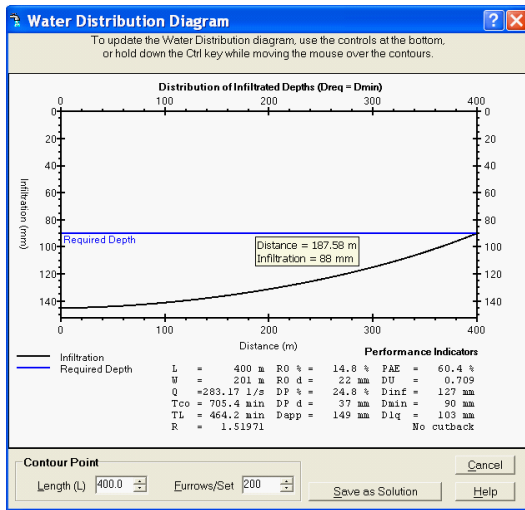
The Water Distribution Diagram shows the infiltration profile and performance summary at the solution point. Navigate the mouse over the PAEmin contour region (with the CTRL key pressed) to view the change in infiltrated profile with changes in length and width.

The second scenario, Sloping Furrow w/Cutback, assumes a cutback rate equal to half the inflow rate which is typical in cutback irrigation. The resulting PAEmin contour graph is depicted in below.
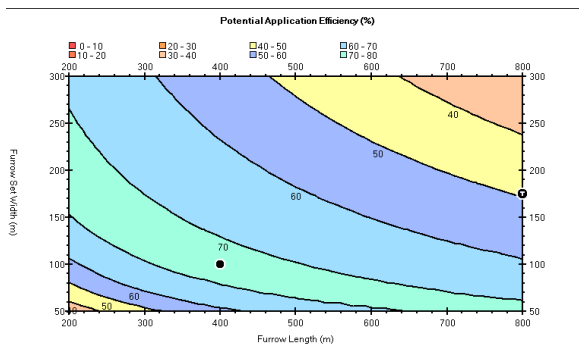
PAEmin increases by about 10 percentage points with cutback under the given conditions, in comparison with the first scenario with no cutback. The region of high performance is also narrower than with cutback and requires a smaller number of furrows (hence, a higher initial inflow rate per furrow). For this example, solutions near the upper-right hand corner of the contour graph do not require cutback; WinSRFR identifies those design variable combinations that do not require cutback while navigating over the contours with the cursor.

The third scenario, Sloping Furrow w/o Cutback, Width Given, was developed to illustrate the use of the second Contour Option, which is to plot length and inflow rate for a specified furrow set width. The example analyzes a single furrow and, thus, the width is set to 1 m (since furrow spacing is also 1 m).
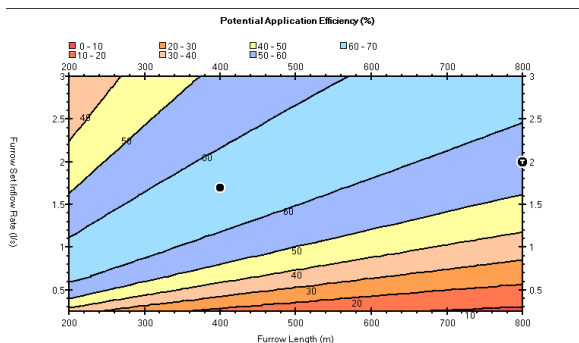
The PAEmin contour graph for this scenario shows that an increasing flow rate is needed to attain high performance with increasing furrow length. Of note is the fact that for a given furrow length, there is a range of flow rates (and associated cutoff times) that will produce near maximum performance, in this case represented by the 60% efficiency contour, and satisfy the Dmin = Dreq requirement. For a furrow length of 400 m, this range is between 1.2 and 2.15 l/s.

The reader is encouraged to inspect the DUmin, RO, and DP contours for this example to assess the impact of inflow rate on distribution uniformity, runoff, and deep percolation. The selected solution point balances runoff and deep percolation losses and provides some insurance against differences in actual field conditions from those assumed in the analysis.

Level Furrows
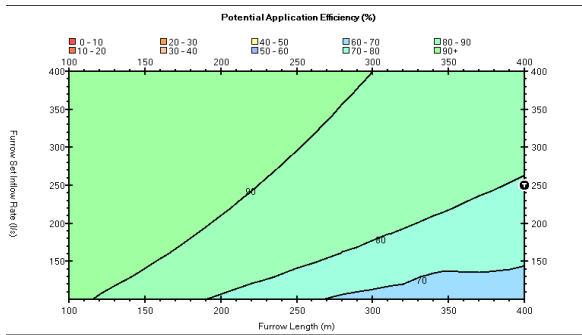
The PAEmin and DUmin contours for this example suggest that very high performance can be achieved under a wide range of length and inflow rate combinations. However, as with the blocked border case, a major concern is the possibility of overtopping the furrow so the range of practical solutions is more limited than suggested by the contours alone. The software currently does not provide feedback on this factor so individual solution points need to be selected and tested in the Simulation World, to determine the maximum flow depth.

Uncertainty of Inputs

The above presented examples are based on the given infiltration and roughness characteristics. Those properties are uncertain and can be expected to vary from furrow-to-furrow (or border-to-border) and from one irrigation event to the next. These results should not be used to develop design recommendations without additional analyses. Sensitivity analyses need to be conducted to test the effect of likely variations in field inputs from the conditions assumed in the initial calculations. For examples, see the training file "Introduction to WinSRFR" and the technical journal article "Analysis of Surface Irrigation Systems with WinSRFR - Example Application" (Bautista et al., 2009).

4.4.2   Basin / Border Design

This example, as well as the preceding Furrow Design, are taken from:

Clemmens, A.J. 2007. **"Simple approach to surface irrigation design: Theory"**
eJournal of Land and Water, Vol. 1, 1-19

Clemmens, A.J. 2007. **"Simple approach to surface irrigation design: Spreadsheet applications"**
eJournal of Land and Water, Vol. 1, 20-43

Both papers and their accompanying Excel spreadsheet applications can be found at:

http://www.sakia.org/ejlw_2007_01_01_i
http://www.sakia.org/ejlw_2007_01_02_i

5.3 Sloping Border Strips

This example is based on section 5.23 Sloping Border Strips and the Excel spreadsheet:

ejlw_2007_01_02_clemmens_border_design.xls
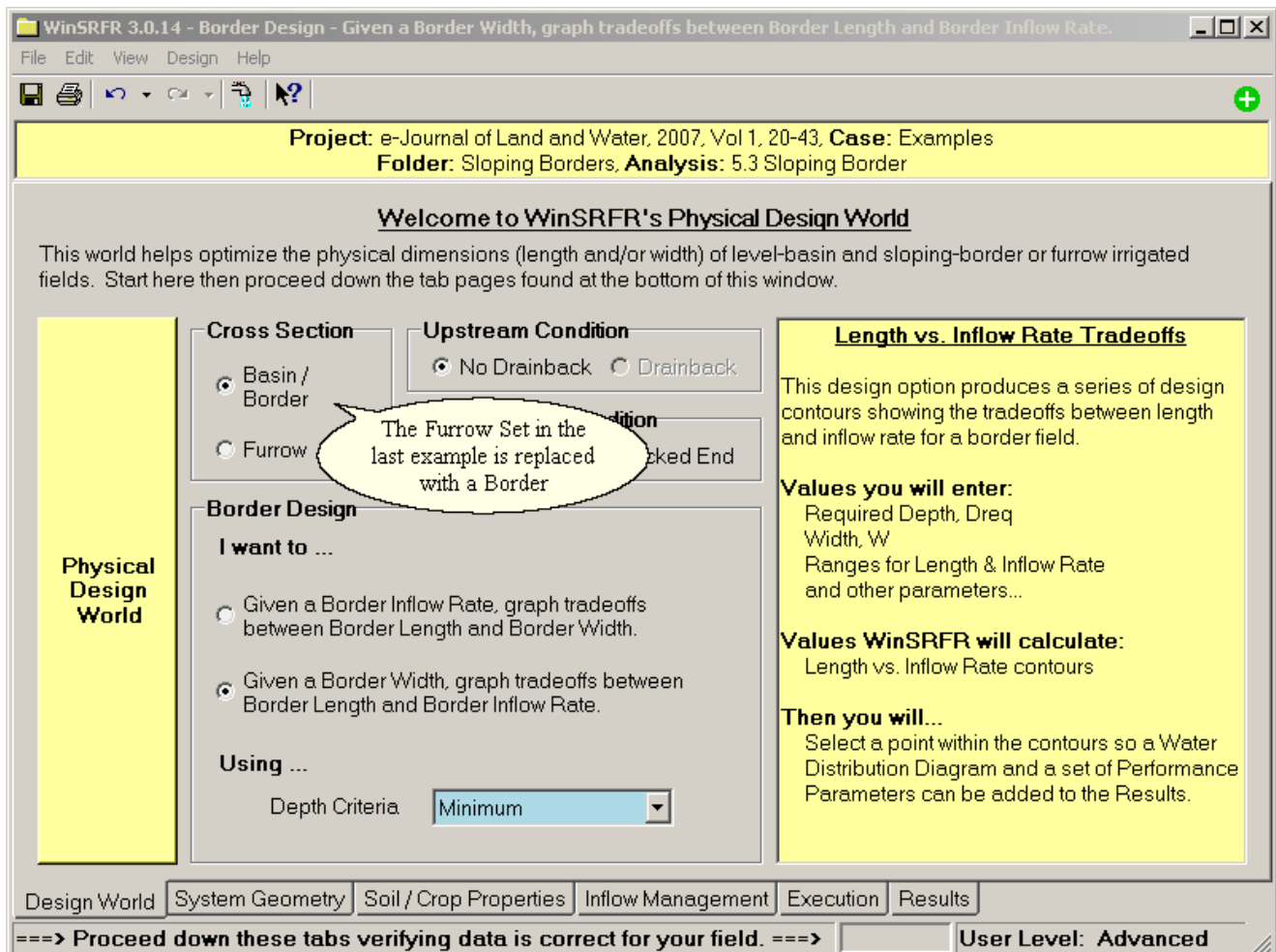
4.4.2.1   Examples

Design examples described herein are provided in the file e-Journal Examples.srfr. The file contains four folders, Sloping Furrows, Sloping Borders, Level Basins, and Level Furrows.

You should work through the Furrow Design examples before proceeding with this example as the inputs, execution control and outputs of a Design Analysis are described in those examples.

- **Inputs** - see Furrow Design Inputs
- **Execution** - see Furrow Design Execution
- **Outputs** - see Furrow Design Outputs

For all border examples, the given slope is 0.2%, the target application depth is 90 mm, and infiltration is given by the Kostiakov function with k = 40.1 mm/hr^a for borders and a = 0.51. A Manning n value of 0.15 for the border/basin cases. It is important to note that the infiltration function given for these problems does not represent the same infiltration characteristics for furrows as for borders/basins.

The examples need to be run to view the results presented below. You may want to inspect the different inputs provided for each example before generating the contours. For each scenario, go to the Execution Tab and press the Estimate Tuning Factors button using the given tuning point and contour ranges. After the tuning calculations are complete, press the Run Design button. To view particular solution points, select them with the Water Distribution Diagram.

Sloping Borders

These examples assume a border width of 100 m and examine the performance as a function of length and inflow rate. The scenarios included in this folder compare an open-ended border with a close-ended one. Contour graphs were generated for the same plotting ranges (200-800 m and 100-400 l/s) and the same tuning point (600 m, 250 l/s). PAEmin contours are shown for these two scenarios. As expected, better PAEmin can be attained with a closed system than with an open one. The difference in PAEmin is due mostly to the runoff losses, which are avoided with the closed system. Note, however, the range of flow rates that will deliver maximum performance is narrower with the closed system than with the open one. For either case, the same length and inflow rate combination could be recommended (identified by the selected solution point), but with a smaller cutoff time for the closed system.
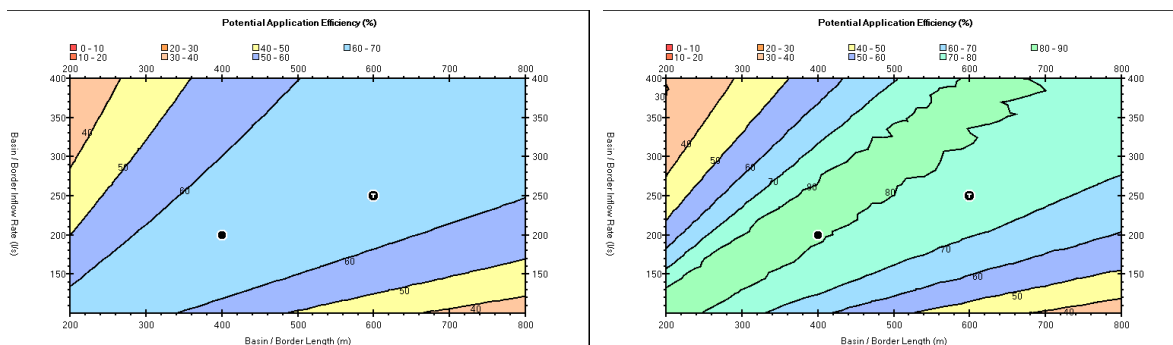
An important feature of solutions for closed ended systems is that the recommended design may not produce a minimum depth at the downstream end of the field, as is typically the case with open systems. This is illustrated with the selected solution point for the close-ended scenario. In this case, the point of minimum infiltration is at about 335 m and most of the deep percolation occurs at the downstream end. In other cases, the point of

minimum infiltration can be located at the upstream end of the field. Changes in the infiltration profile with length and inflow rate can be easily examined with the Water Distribution Diagram, as explained previously. The large percolation losses at the field end for this example are also an indicator of large flow depths which can potentially overtop the border berms. The Physical Design output currently does not include flow depth information, however when saving the solution point, WinSRFR will produce a beep to indicate that the default border berm/furrow height has been exceeded. An unsteady flow simulation can be conducted with selected solution and the resulting depth hydrographs used to assess potential overtopping problems.

Level Basins

Basin design is different from the previous two examples in that WinSRFR plots results only for combinations of the design variables that result in advance ratios R greater than 0.85. With level systems, there is significant risk that water will not reach the end of the field when the advance distance at cutoff time is less than 85% of the total length. This limit was developed from theoretical simulation studies.
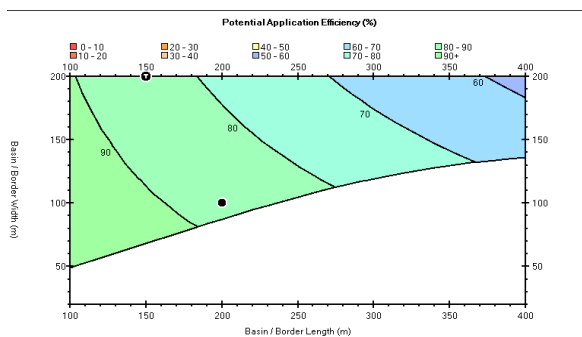
This figure illustrates the PAEmin contour graph for the Level Basin Example. The white area represents solutions that would require an R < 0.85. Navigating with the cursor over this area will generate a message that the limit line has been exceeded. A contour graph for R is also generated as part of WinSRFR's output and should be examined to get a better understanding of R for different variable combinations.

In comparison with the sloping border case, the level basin design requires a shorter field length to attain maximum performance. However, high performance can be maintained with a wider range of flows, at least for the infiltration conditions of this example. Under the given conditions, PAEmin and DUmin in excess of 90% are attainable, but only if the length is less than about 180 m.

Note the location of the tuning point. With level basin systems, finding an appropriate calibration point may be more challenging than with other systems. The software will not allow a calibration point to be located in area where the R <> 0.85 and will suggest an alternate location.

4.5   Operations Analysis

Overview

The Operations Analysis World is used to optimize system inflow rate and cutoff time. Similar to the Physical Design World, Operations Analysis generates performance contours as a function of the decision variables using volume balance calculations calibrated by zero-inertia simulation results. For a given physical layout and set of infiltration and hydraulic resistance conditions, different combinations of discharge and cutoff time will produce different infiltration profiles and not all why satisfy the irrigation requirement. The contours are used to find discharge-cutoff time combinations that will match either the minimum or the low-quarter infiltrated depth to the irrigation requirement. See [Surface Irrigation Design](#) for more information.

Applicability

The Operations Analysis World is used to analyze furrows, borders, and basins, either with an open or closed downstream end. Procedures are applicable to graded or level systems, but calculations assume a uniform field slope. The analysis can be conducted assuming a constant inflow rate or a flow cutback strategy (furrows).

4.5.1   Basin / Border / Furrow Operations

Operations World Tab

The irrigation system type, (furrows or borders/basin) and the downstream boundary condition need to be specified in this tab. In Operations Analysis, the only Contour Option is to plot performance as a function of discharge and cutoff time. The Depth Criteria drop-down box determines whether the software generates contours for Dmin (minimum depth) or Dlq (low-quarter depth) as a function of the decision variables.
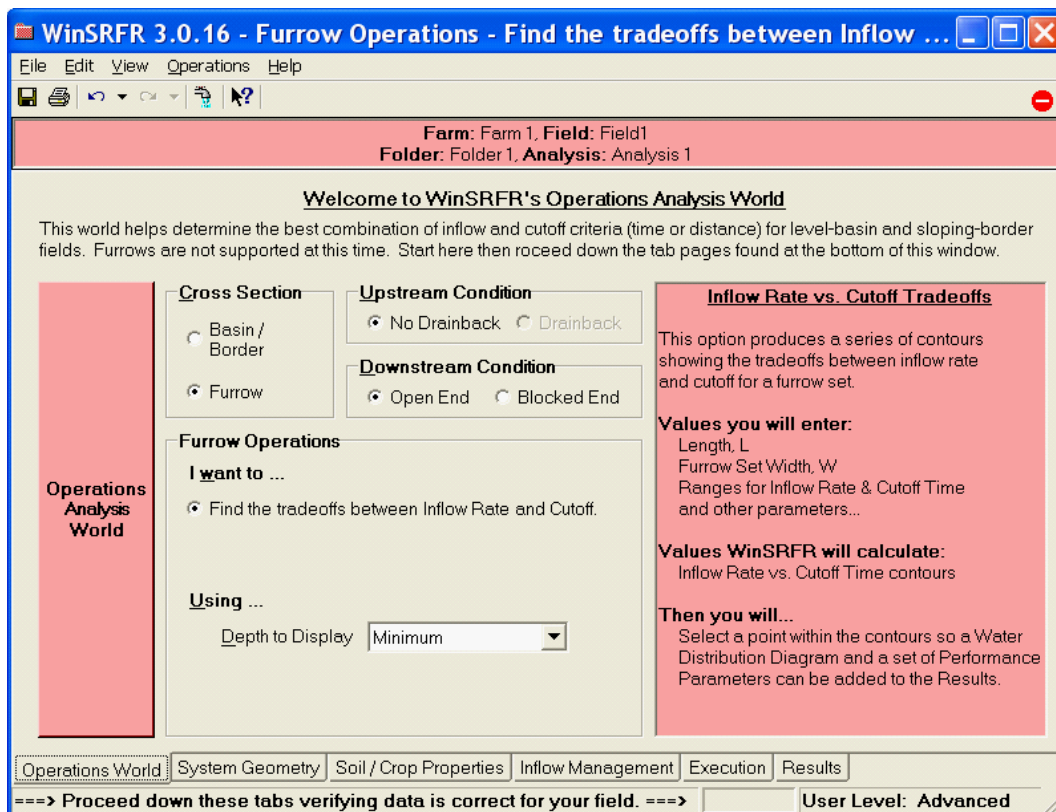
4.5.1.1 Inputs

Common Inputs

System Geometry tab

Input	Input/Output	Use
Length	Input	
Width/Set Width	Input	
Maximum depth	Input	Used indirectly, the simulation engine (which is used in calibration and when computing a solution point)
Slope	Input	Design analysis assumes a constant slope, which can be given as a single value, or calculated from a user-entered table of elevations (slopes) with distance

Soil / Crop Properties tab

Input	Input/Output	Use
Hydraulic Roughness	Input	Design analysis uses only the Manning roughness option, user-entered or selected from a table of NRCS recommended values
Infiltration	Input	With borders/basins, any infiltration formula used by WinSRFR's simulation engine can be selected. With furrows, design analyses uses restricts the infiltration function choice to Kostiakov, Modified Kostiakov, and Branch functions and the wetted perimeter options to furrow spacing.

Inflow / Outflow tab

Variable	Input/Output	Use
Unit Water Cost	Input	Not used
Required Depth	Input	Solutions match the minimum infiltrated depth to the required depth, Dmin = Dreq
Inflow Method	Input	A standard hydrograph is the only available option
Inflow Rate	Output	The text box displays the inflow rate associated with the selected solution point
Cutoff Options	Input	Time-based cutoff is the only available option
Cutoff Time	Output	Calculated value, text box will display the cutoff time of the selected solution point
Cutback Options	Input	With furrows, the design can be based on constant inflow or inflow with cutback; option unavailable for borders/basins
Cutback Time	Output	Text box displays cutback time for the selected solution point
Cutback Rate	Input	The entered value is multiplied by the initial inflow rate to determine the cutback rate

4.5.1.2 Execution

Execution Tab

The Execution Tab displays four sets of inputs, one of which is non-selectable by the user.
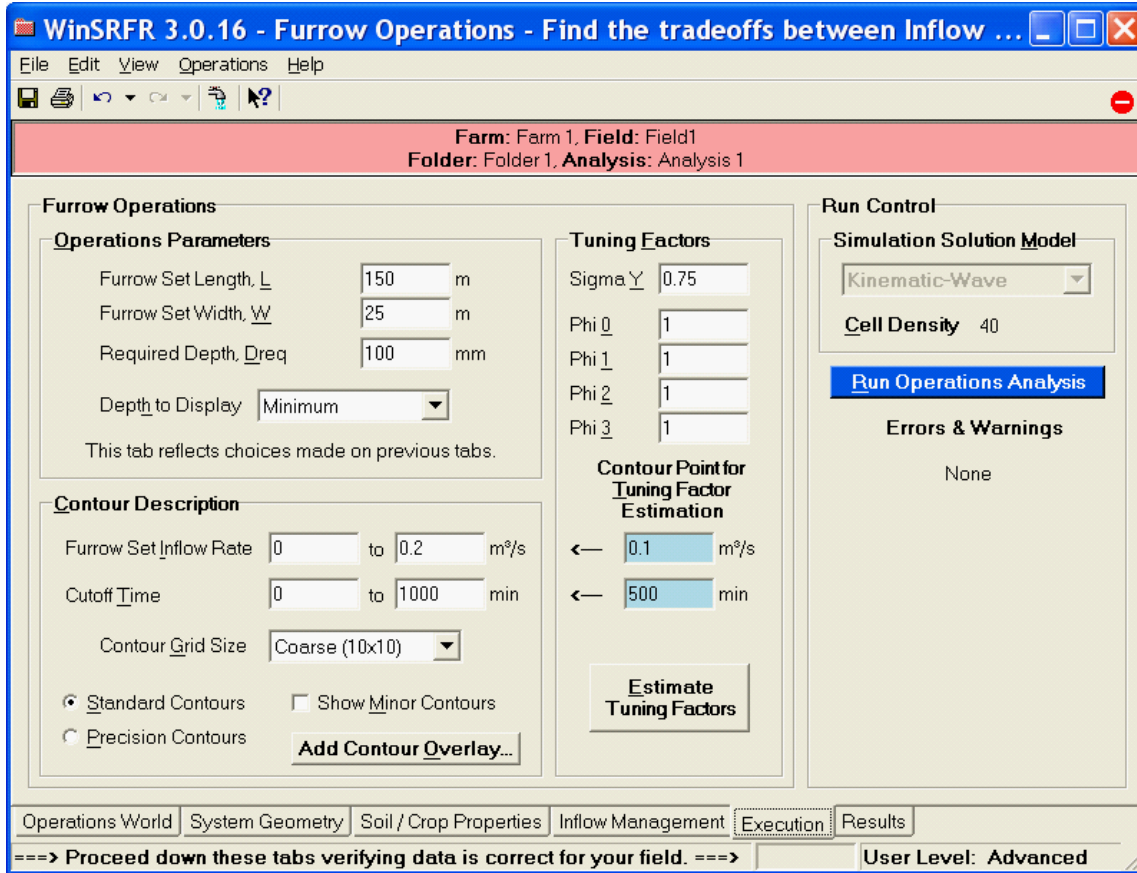
In the **Operations Parameters** section, you can modify the physical dimensions of the system and the required infiltration depth, Dreq. The Depth Criteria, as provided in the Operations World tab, can also be edited (minimum or low-quarter).

Contouring parameters are specified in the **Contour Definition** section. A key input is the range of the decision variables to be examined, Inflow Rate vs. Cutoff Time. This range is defined by minimum and maximum values. Development of an acceptable contour graph for a specific problem can take a few iterations — 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. Other inputs required by this section are explained in the Physical Design section.

Calibration of the volume balance results are controlled by the inputs provided in the **Tuning Factors** section. These inputs are similar to those described in the Physical Design section, except that the tuning point is a flow rate and cutoff time combination. For Operations Analysis, the recommended placement of the tuning point is in the middle of the contour region. After editing these values, press the Estimate Tuning Factors button. WinSRFR will run through a series of unsteady flow simulations to complete the calibration process. If the tuning is successful, the program will display completion messages and the computed tuning parameters will be displayed in the boxes labeled Phi0-Phi3. Otherwise, the program will suggest an alternative location for the

tuning point or ask the user to provide an alternative location. NOTE: the tuning calculations are specific to the given set of inputs. While WinSRFR will rerun the design computations without recalibrating, changes to any particular input invalidates the existing tuning results. Also, different combinations of tuning factors are computed depending on the type of irrigation system. Furrows use Phi0-Phi3, borders Phi0-Phi4, and level basins Phi0-Phi1.

The **Run Control** identifies the simulation engine used for calibration, zero-inertia or kinematic wave. This choice is set by the program and is, therefore, disabled but displayed for informational purposes. After completing the tuning process, press the Run Operations Analysis button. The program will then compute the contours. Messages indicating the progress of the calculations will be displayed at the bottom of the Execution tab. If the calculations are successful, WinSRFR will display the computed contours. Some computational problems will cause WinSRFR to display warning/error messages. Those messages mostly relate to solution regions that do not satisfy the problem's requirements (mostly related to advance to the end of the field). Those messages are provided for informational purposes and can be closed to allow the program to display the contours.

4.5.1.3 Outputs

Results Tab

The outputs of the operations analysis, described in following table, are displayed by the results tab. For mathematical descriptions of these outputs, see the Terminology section, in Technical Background.
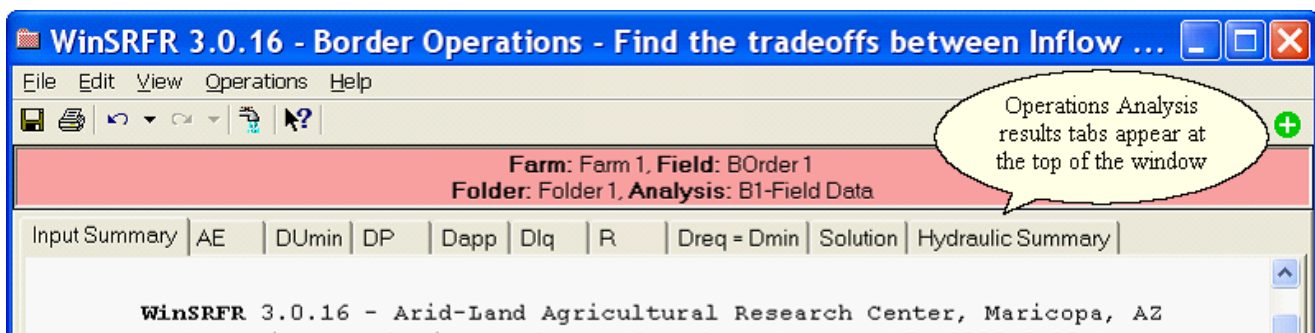
Summary of output tabs

Tab	Type	Description
Input Summary	Table	Summary of inputs
AE	Contour graph	Application Efficiency
DUmin	Contour graph	Distribution Uniformity of the Minimum
RO	Contour graph	Runoff
DP	Contour graph	Deep Percolation
Dapp	Contour graph	Applied Depth
Dmin or Dlq	Contour graph	Minimum or Low-quarter infiltrated depth

R	Contour graph	Advance Ratio = • Advance Distance at Cutoff Time/Length if R = 1, • Cutoff Time/Final Advance Distance Time if R>1
Solution	Graph	Final infiltrated profile and performance summary for the selected solution point
Dreq=Dmin	Graph	Graph that illustrates the application efficiency and cutoff time of the set of solutions satisfying the Dmin = Dreq condition
Hydraulic Summary	Graph	Comparison of volume balance and unsteady flow simulation predictions for the selected solution point. Overlaid outputs include • Plot of advance/recession times with distance, • inflow and outflow with time, • plot of final infiltration depth with distance

Adjusting contour display options

WinSRFR offers various choices for displaying the performance contours. Those display options can be edited from the Edit/User Preferences command. More details are provided in Contours User Preferences.

Navigating the contours

The same tools can be used to navigate the performance contours in the Operations Analysis World as in the Physical Design World. Selecting a solution point with the Water Distribution Diagram updates the Solution and Hydraulic Summary tab sheets. The Hydraulic Summary tab can be used to assess the accuracy of the volume balance calculations in comparison with unsteady flow simulation results. For further details, see the Physical Design section.

Contours

Using contours, the Design World shows tradeoffs between Length and Width or Inflow Rate while the Operations World shows tradeoffs between Inflow Rate and Cutoff Time. The user can use the contours to choose the best irrigation scenario. The algorithms that calculate the contours are calibrated with the SRFR Simulation using Tuning Factors at a single point within the contours. This tuning point is depicted on the contours as a black circle with an embedded "T".

The user can choose a Solution Point, depicted as a black circle, to have further analysis performed on. The Solution Point analysis is displayed using the Solution and Hydraulic Summary tabs. The Solution Point can be chosen either using the right-click context menu within the contours or by using View or Operations menu items.
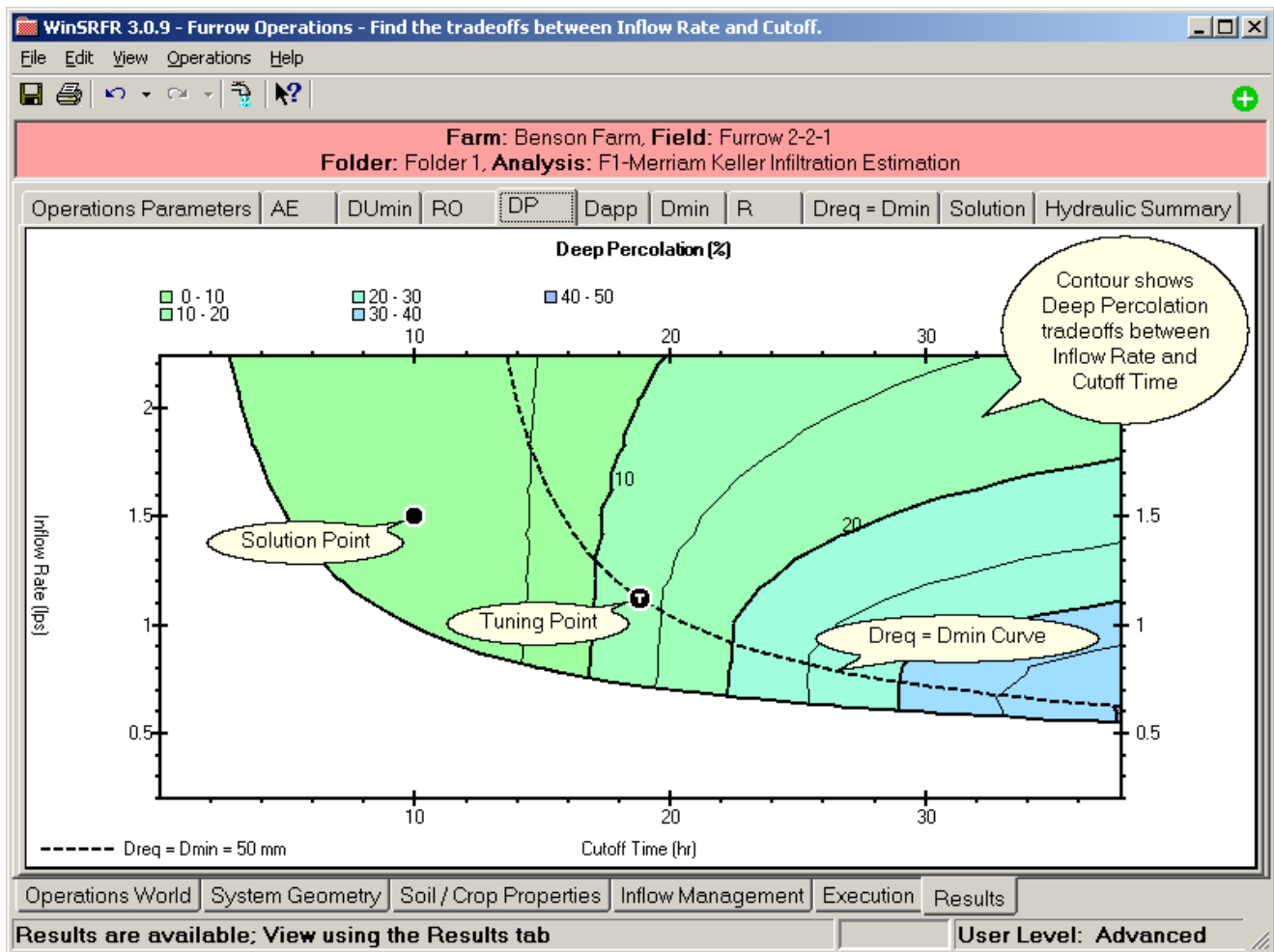
Dreq = Dmin/Dlq Graph

The Operations World produces an additional graph showing the relationship between Application Efficiency (AE) and Inflow Rate (Qin) and Cutoff Time (Tco). The curves represent points from the contours where Dreq = Dmin or Dreq = Dlq depending on the **Depth to Display** choice made by the user. The Dreq = Dmin/Dlq curve is also shown on all the contours. Any point along these curves can be chosen as a Solution Point; the advantage of using this graph to choose the Solution Point is that Dmin/Dlq = Dreq at every point. While the Choose Solution Point dialog box is displayed, you can hold down the Ctrl key while moving the mouse over the Dreq = Dmin/Dlq graph to see the Water Distribution Diagram along these curves.
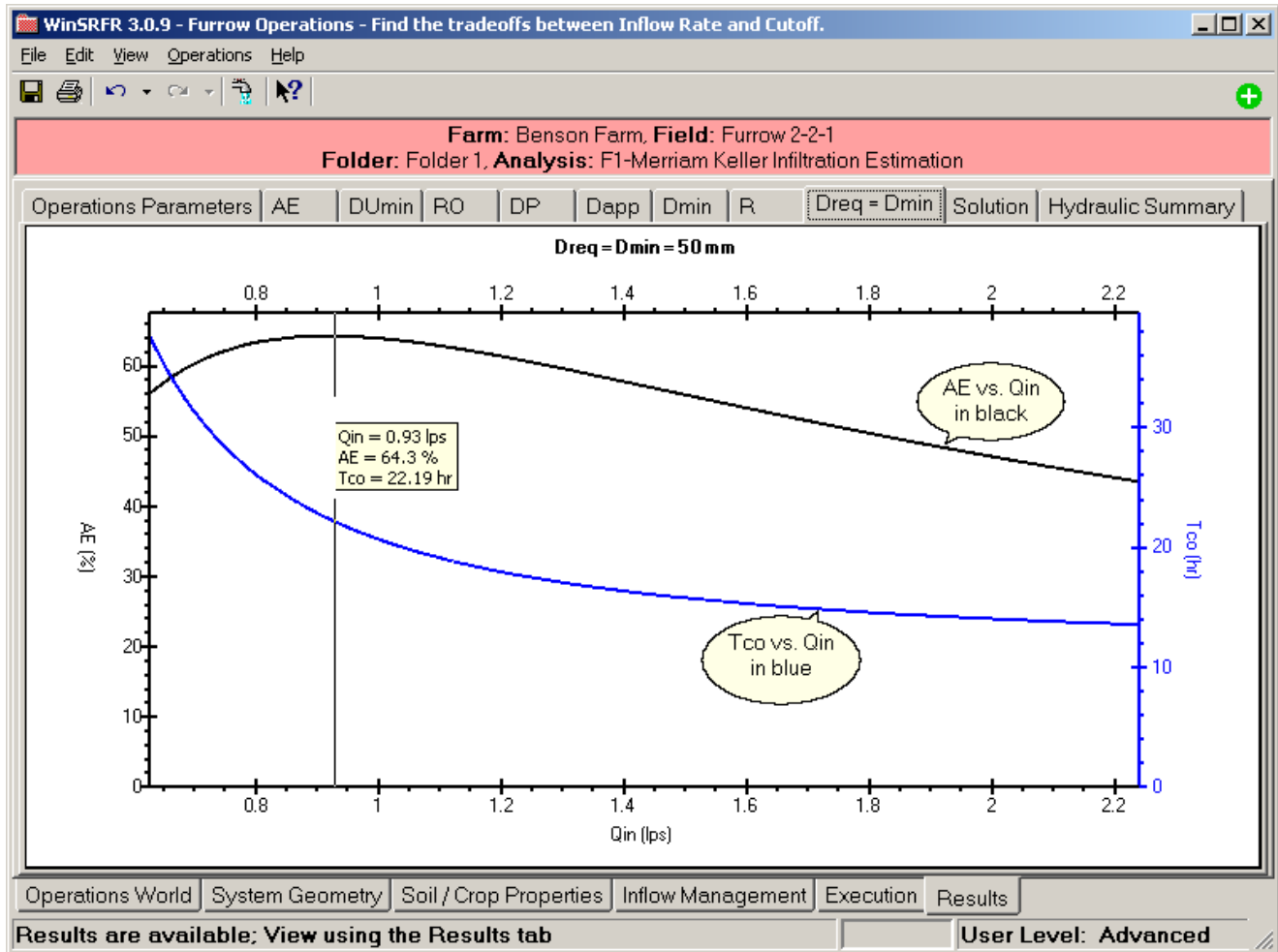
Contour Overlay

When working in the Design or Operations Worlds, you can add an Overlay Tab to the Results. The Overlay Tab combines the contour curves from the selected parameters.
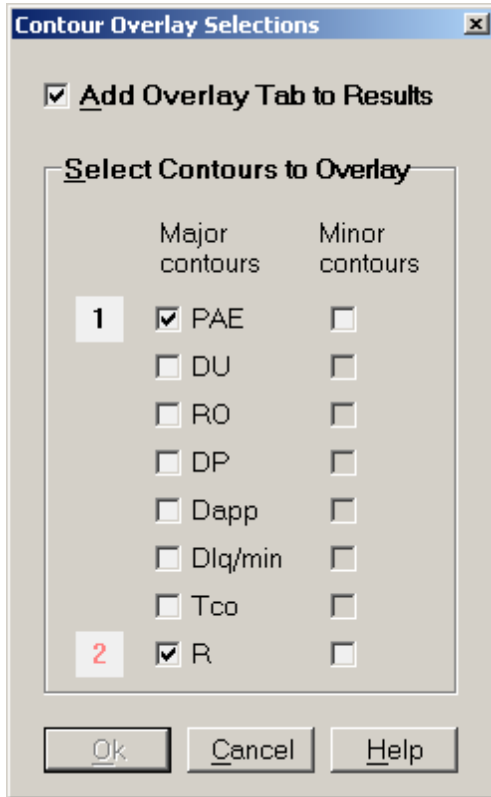
1. Use the '**Add Overlay Tab to Results**' check box to enable or disable the Overlay Tab.

2. Select the **Major / Minor contours** to add to the overlay. The order of selection defines the color used to plot the curves; see the left column of numbers. Each number displays the color that will be used to draw that contour. The colors are chosen using the User Preferences Graphs tab.

The selections made in this dialog box resulted in the Contour Overlay shown below being added to the Results.
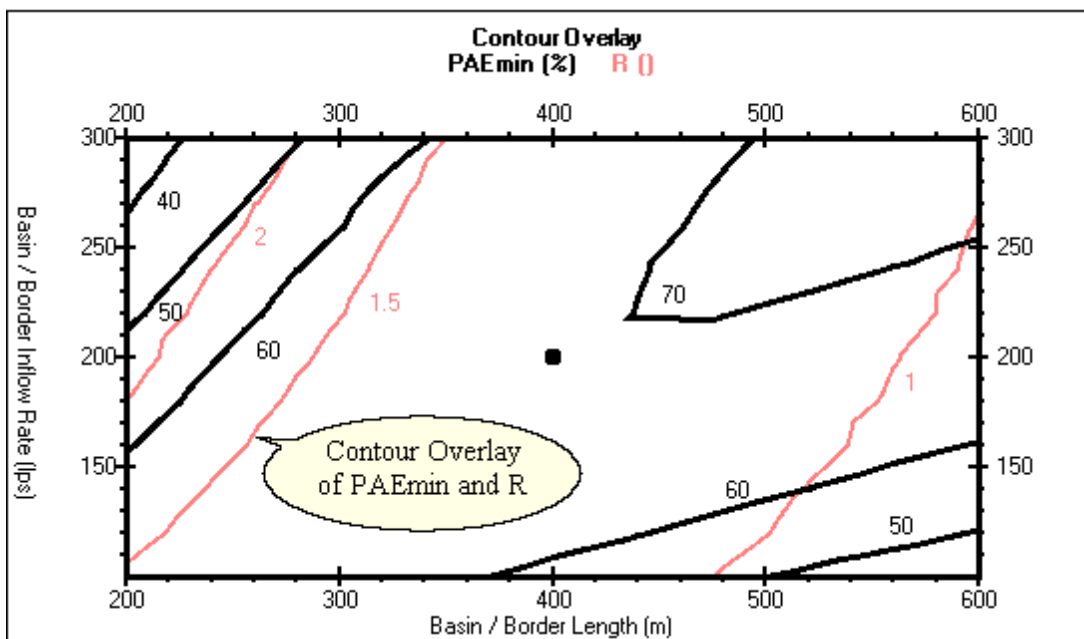
Solution Point

After a Solution Point is chosen using the contours or the Dreq = Dmin graph, an analysis is performed on that point and the results displayed using the Solution and Hydraulic Summary tabs.
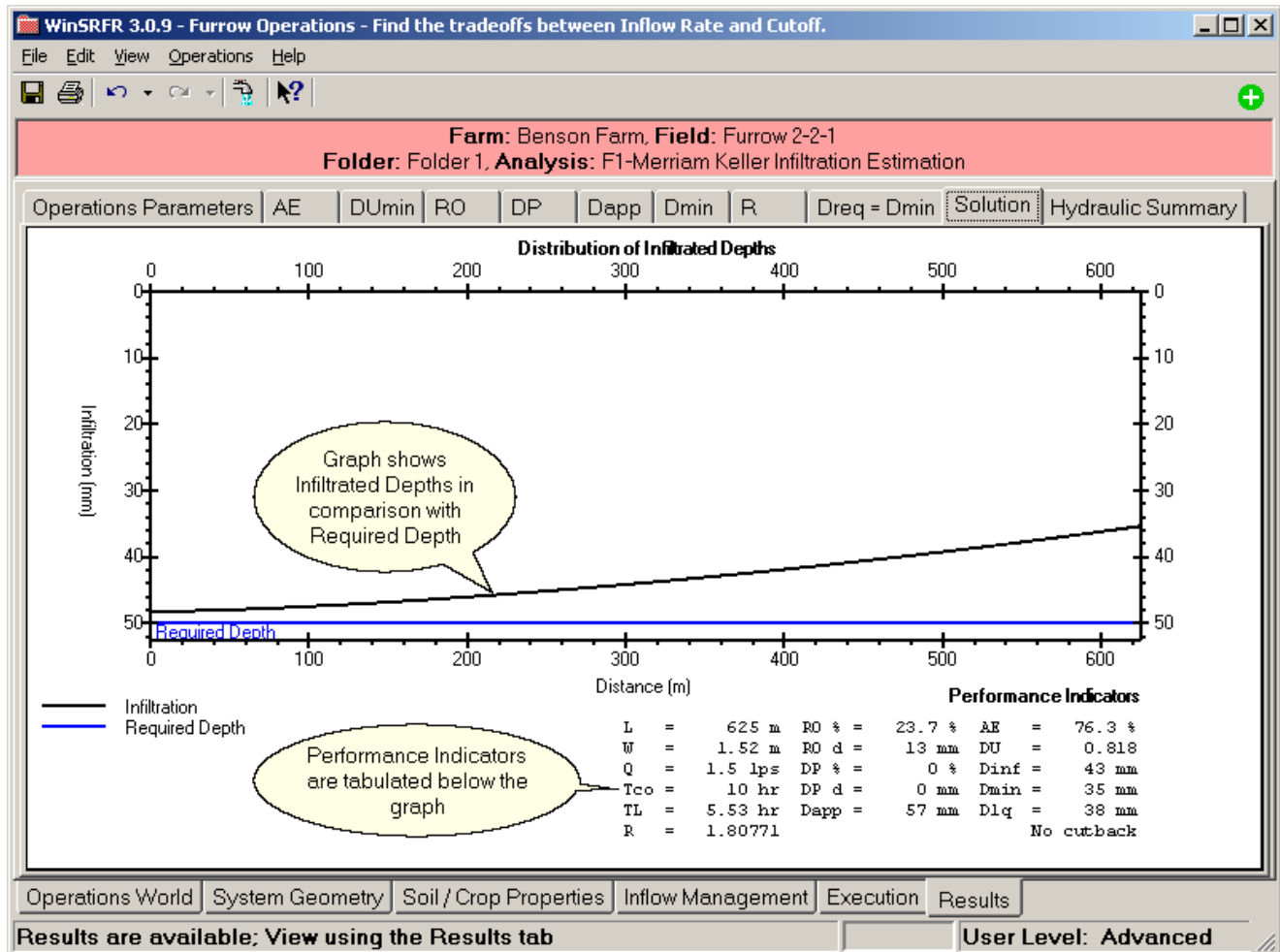
Water Distribution Diagram

When working with fields in either the Physical Design or Operations Analysis Worlds, a Run produces contour graphs of many possible solutions for your irrigation needs. To evaluate a single solution, use the Choose Solution Dialog Box that displays a Water Distribution Diagram to view then select a single point within the contours.

A Water Distribution Diagram and Hydraulic Summary for this point will then be added to the Results if you choose **Save as Solution**.
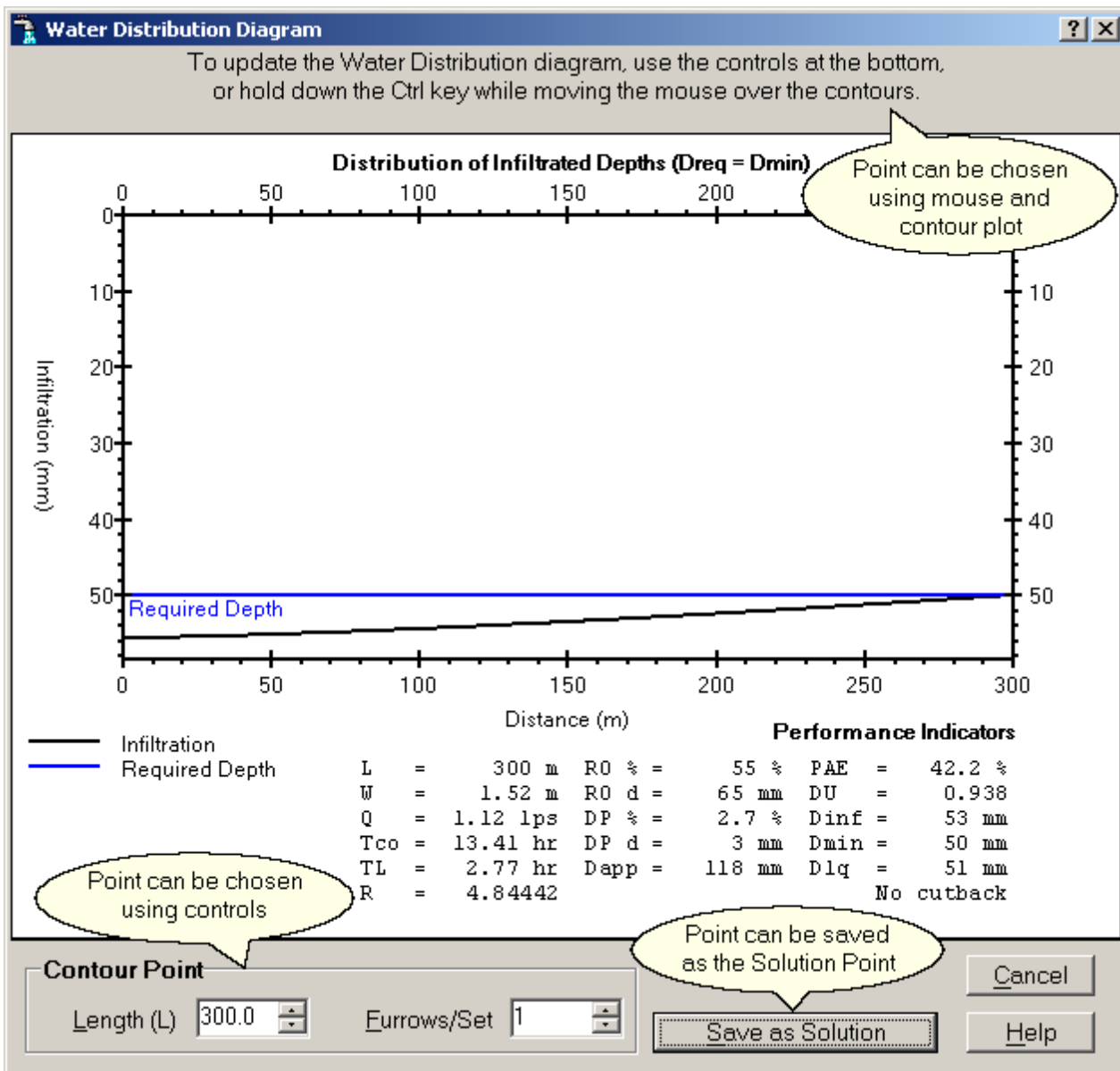
Changing the **Contour Point** values either manually or by moving the mouse over a contour while holding down the Ctrl key will update the Water Distribution Diagram for the newly selected contour point.

4.5.1.4   Examples

A series of operational analysis scenarios are presented in the "Operations Analysis.srfr" file. All of the scenarios in this file need to be executed by pressing first the Estimate Tuning Factors button and then Run Operations Analysis button in the Execution tab.

The system is 1968 ft long X 131 ft wide (600 m X 40 m), with a slope of 0.002. The border is assumed to have a roughness of 0.15 (alfalfa) and infiltration properties given by the NRCS 0.6 Infiltration Family, with a target application depth of 90 mm. The border is irrigated for 4 hours when the maximum flow is available, 10 cfs (~285 l/s) but the supply rate can be less than the conveyance system capacity, sometimes as low as 6 cfs (170 l/s). Assuming 12 identical borders in the field and a maximum of 48 hours to irrigate the field, the analysis aims to determine:

- The maximum application that can be attained with the existing system, and the time needed to irrigate the field with the optimal rate.

- How will management options and performance change if a blocked end is added to the current system.

The scenario "Existing border, open end" analyzes operations with the current system. The calibration point is located in the middle of the contour region. Although the maximum available inflow rate is 12 cfs, the contours were developed for a slightly greater flow range, to illustrate some hydraulic characteristics of the system.

The left figure below depicts the Application Efficiency contour for this initial scenario. In the graph, the dotted line represented the solutions that satisfy the Dmin=Dreq criteria. Clearly, AE cannot exceed ~ 63% under the given conditions. The Dmin = Dreq curve in the right figure shows that for inflow rates greater than ~ 11 cfs, the cutoff time is near constant, about 3.3 hrs. This is because with very high flow rates the advance time to the end of the field is less than the opportunity time needed to infiltrate the irrigation requirement at the upstream end, 3.54 hrs (the opportunity time for the requirement is illustrated with the infiltration curve in the Soil/Crop Properties Tab).   The irrigation requirement cannot be satisfied everywhere if the cutoff time is less than the opportunity time for the irrigation target. Use the Water Distribution Diagram to examine the behavior of the infiltration profile along the Dmin = Dreq line. For flow rates less than cfs, the point of minimum infiltration is located upstream, while for flows less than 11 cfs, it is downstream and cutoff time increases as flow rate decreases. The current operation is identified in the graph and results in an AE of about 53%.
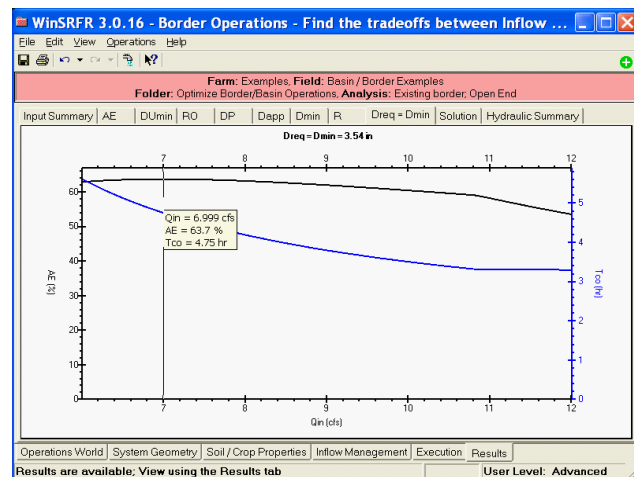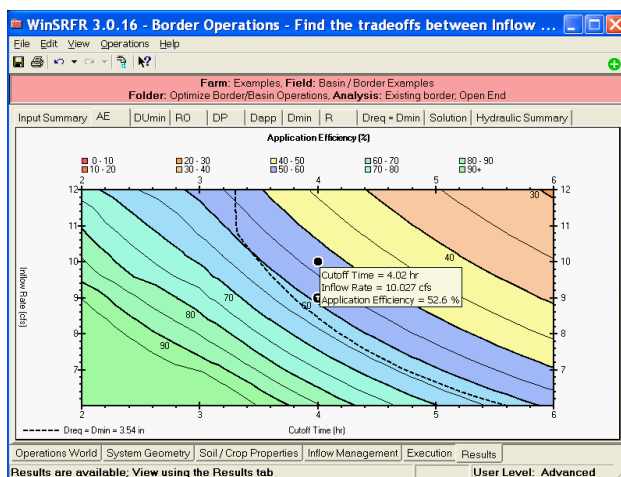
Solutions satisfying the Dmin = Dreq criteria can be more easily inspected with the Dmin = Dreq graph. You can navigate this graph just as you would navigate the performance contours and get more detailed information on the Q-tco combinations of interest. If you right click on a selected point, you will bring up again the Water Distribution Diagram. By pressing the CTRL key, you can navigate the Dmin = Dreq graph and dynamically updated the Water Distribution Diagram. The illustration shows the point of maximum AE (63.7%), corresponds to a discharge of 7 cfs and a cutoff time of 4.76 h. This means that the entire field cannot be irrigated with the optimal flow rate within the 48 h period. However, the entire field can be irrigated with AE = 62% when applying 8.45 cfs and a cutoff time of 4 h.

The Blocked End scenario only changes the downstream boundary condition relative to the previous example.
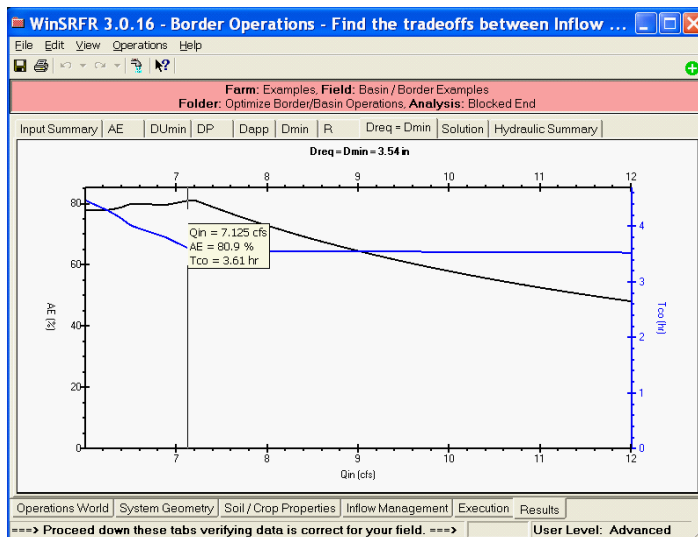
The Dmin = Dreq graph for this scenario is shown in this figure. As with the open-ended case, there is a flow rate (about 7.2 cfs) beyond which cutoff time is relatively constant while AE decreases. With the blocked end, efficiencies near 80% are attainable, even with the smallest available inflow rate. However, a flow rate of 6.5 cfs is needed as a minimum to irrigate the border in 4 hrs. With this configuration, maximum performance can be achieved with a discharge of about 7.2 cfs and a cutoff time of 3.6 h.

Use the Water Distribution Diagram to examine the behavior in infiltration profile with different inflow rate-cutoff time combinations. A potential problem with the use of a blocked end is the fact that deep percolation losses are extreme at that end of the field and that berm height has to be set as a function of the maximum flow depth. Use the Dmin = Dreq graph to select the combination of maximum performance and then examine the resulting infiltration profile for that solution point. Also, copy that solution point into to the Simulation World and from the simulation results, examine the depth hydrographs. The required berm has to be more than 8 in high, since the predicted water depths exceeds 8 in at the downstream end.

4.6   Erosion Simulation

Overview

THIS FEATURE HAS BEEN DISABLED FOR VERSION 3.1

Erosion simulation, available for Advanced Users of WinSRFR, enables calculation of furrow-soil detachment and entrainment into the furrow stream, transport downstream, and deposition at points of low flow velocity, in response to the simulated furrow flow and soil properties. Following the simulation, WinSRFR displays hydrographs of the calculated mass transport across sections located at the quarter and end points of the subject furrow. The post-irrigation net soil loss upstream from each quarter point and in the runoff is presented in metric Tons per hectare on the output page together with the hydraulic performance parameters for the simulated irrigation.

Sediment components: the mix of grain sizes prevalent in the furrow soil is entered in the table in terms of the fraction of the mix coarser than a given size. Commonly, the mix is specified as percentages of sand, silt, and clay. The larger sizes are retained on sieves with a given size of perforations, e.g., sand can be considered to consist of particles that will not pass through 50 micron openings, i.e., are retained; silts pass through a 50 micron sieve, but are coarser than 8 microns (the very small particle sizes are too small for mechanical sieving, and their fraction is determined by standard pipette techniques based on fall velocities and Stokes' Law). The fraction (100% - % sand - % silts) of the mix smaller than 8 microns can be considered clays. The components can be entered directly into the table or entered using the Sand / Silt / Clay Dialog Box.

If data are available, the specific gravity of the particles can be entered, replacing the default 2.65.
Water temperature affects its viscosity and sediment fall velocity, and is entered in the pertinent dialogue box.

The Simulation World requires user entry of **soil erodibility and critical shear.** Erodibility, KR, is a site-specific field-soil property describing the susceptibility of the soil mix to entrainment into a furrow stream of clear-water exerting shear on the soil (the presence of sediment in the flow reduces its ability to entrain more). KR is the mass entrained per second per square meter of soil surface, divided by the stream shear in excess of the critical shear, TauC, (also a site-specific field property) raised to a user-specified power (typically, unity, in the absence of information to the contrary). Shear stress less than critical precludes *any* entrainment. WinSRFR can suggest a value of critical shear based on a "representative particle size," derived by WinSRFR from the mix of sizes entered (50% of the mix is larger/smaller than the "representative" size).

In the event that field data on soil erodibility is not available, WinSRFR can suggest a value based on a single measurement of sediment concentration (grams per liter) in a test-furrow flow at the quarter point of the furrow at a user-specified representative time. This information is entered in the Event Analysis World, in a data-input screen similar to the one in the Simulation World, except that the field erodibility parameters are left "to be determined," and data slots are made available for the measured concentration data. When the analysis is completed, the resultant values of erodibility and critical shear appear in the appropriate windows. The information can be used for subsequent simulation studies by copying the data from the event folder (in the Project Management window) and pasting into a simulation folder.

In performing either simulations or evaluations, WinSRFR utilizes a theoretical, continuous particle-size distribution based on the discrete sediment components entered in the table. In the input dialogue, the user can select a finer or coarser resolution in the theoretical distribution that is fitted to the entered size data -- with either a Gauss normal, or piece-wise linear (recommended) fit.

4.6.1 Inputs

Erosion Tab

Provide four input section:

- Sediment Components
- Particle Size Distribution
- Irrigation Water
- Soil Erodibility

Prior to estimating the Soil Erodibility parameters or running an erosion simulation, the Sediment Components that make up the field's soil must be entered. The components can be entered directly into the table or entered using the Sand / Silt / Clay Dialog Box.

When estimating the Soil Erodibility parameters, a single field measurement must be made during an irrigation. The amount of soil in grams per liter that is contained by the irrigation water must be measured 1/4 of the distance down the field at a representative time during the irrigation.

4.6.2   Execution

Refer to Hydraulic Simulation Execution.

4.6.3   Outputs

Four additional graphs are added to the Results when Erosion Simulation is selected:

- Hydrographs (Erosion G) - flow of sediment as mass sediment / time
- Hydrographs (Erosion CGm) - flow of sediment as mass sediment / volume water
- Hydrographs (Erosion CGv) - flow of sediment as volume sediment / volume water
- XTICS Net

The locations for the curves are selected using the **Hydrograph Location Table** accessed using the Standard Simulation Criteria dialog.
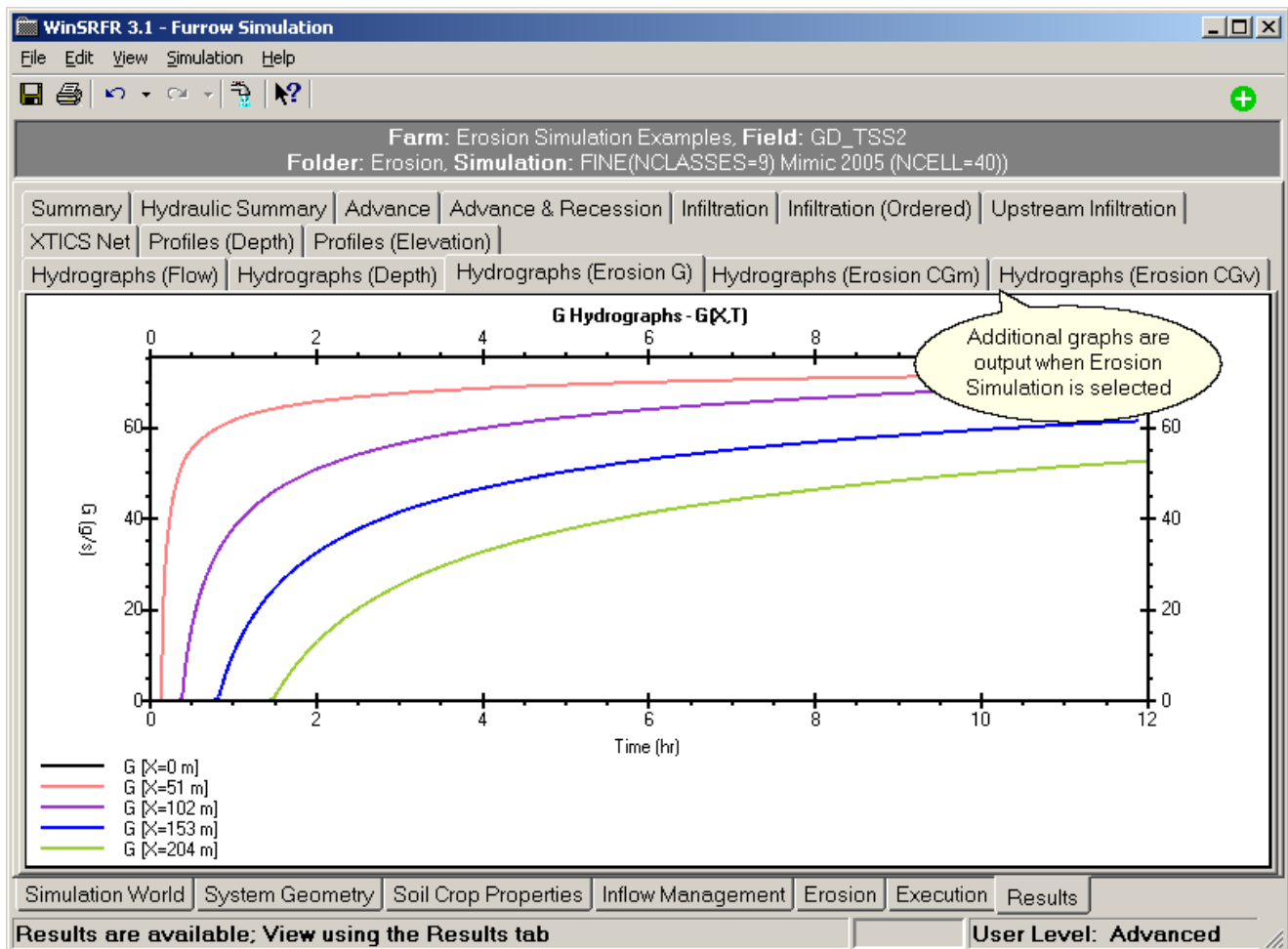
4.6.4   Examples

Examples including erosion simulation can be found in **Erosion-GD_TSS2.srfr**.

5 Technical Background

The U.S. Water Conservation Lab (USWCL) developed several software programs to aid in the efficient design, operation, management and simulation of surface irrigation. Included in this list are:

BASIN   - Level-Basin irrigation design and management
BORDER   - Sloping-Border irrigation design, management and operations
SRFR   - Basin, Border and Furrow irrigation simulation

The newest software program, WinSRFR, combines the features and functions from these three legacy DOS programs while adding new capabilities like irrigation event analysis, furrow design and operations and erosion simulation. Users of BASIN, BORDER & SRFR will notice many similarities in nomenclature, data groupings, selections and output displays. While the functionality provided by these older programs is still valid, WinSRFR moves this functionality into the modern Windows paradigm.

WinSRFR is produced by the Arid-Land Agricultural Research Center (ALARC), the successor to the USWCL. ALARC is part of the USDA's Agricultural Research Service (ARS).

5.1   Infiltration Computation

The following text is reproduced from: Bautista, E; Clemmens, A.J., Strelkoff, T.S.; Schlegel, J.L. 2009. Modern Analysis of Surface Irrigation Systems with WinSRFR. Agric. Water Manage. Accepted for publication.

Infiltration Computations

WinSRFR presently uses empirical formulas for infiltration computations. In a one-dimensional view of the irrigation stream, in which all variables are functions of distance and time only, the pertinent infiltration variable is the volume infiltrated per unit length $A_z(x, t)$ [L^3/L]. The simulation engine calculates A_z as

$$A_z = WP \cdot z \tag{1}$$

In which WP [L] is the transverse length of the soil-stream interface through which the infiltration must take place, and z is the volume infiltrated per unit area of the soil surface [L^3/L^2]. Eq. (1) assumes water infiltrates in a direction normal to the soil surface. This is a reasonable assumption when dealing with border strips and basins, where water infiltrates essentially in the vertically direction and WP is constant and equal to the border/basin width W. Eq. (1) represents furrow infiltration less adequately because of the contribution of horizontal flow to total infiltration, and because WP varies with distance and time as the depth of the stream rises and falls with the passage of the stream. Options for calculating z and WP are discussed next, along with the uses and limitations of these options.

Infiltration functions
Table 1 lists the options provided by WinSRFR for calculating z. In these expressions, the exponent a is dimensionless, and k, b, and c are parameters with dimensions and units consistent with those of z and $\ddot{A}$
Table 1. WinSRFR options for the calculation of infiltrated depth

Name	Equation Form	Equation
Kostiakov Formula (Kostiakov, 1932; Lewis, 1937)	$z = k\tau^a$	(2)
Modified Kostiakov Formula (Mezencev, 1948; Strelkoff et al., 1998)	$z = k\tau^a + b\tau + c$	(3)
NRCS Infiltration Family (USDA-NRCS, 1974; USDA-NRCS, 1984)	$z = k\tau^a + c$	(4)
Known Characteristic Infiltration Time (Strelkoff et al., 1998)	$z = k\tau^a$	(2)
Time Rated Intake Family (Merriam and Clemmens, 1986)	$z = k\tau^a$ with a given by $a = 0.675 - 0.2125\log_{10}(\tau_{100})$	(2) (5)

Branch Function (Clemmens, 1981)	$z = k\tau^a + c, \quad \tau \leq \tau_b$ $z = k\tau_b^a + c + b \cdot (\tau - \tau_b), \quad \tau > \tau_b$ $\tau_b = \left(\dfrac{ak}{b}\right)^{\frac{1}{1-a}}$	(6)

The Kostiakov (1932) equation (Eq. 2) has been widely used in irrigation studies but it can represent the process inaccurately in soils with a well-defined steady-state infiltration rate. Mezencev (1948) recognized this limitation and added to Eq. (2) the product *bt,* with *b* the long-term infiltration rate. That equation, commonly identified in the literature as the Modified Kostiakov equation, was further modified in the SRFR program (Strelkoff et al., 1998), by adding a constant *c* to account for instantaneous macropore infiltration. The USDA- Soil Conservation Service, SCS (now known as the Natural Resource Conservation Service, NRCS) proposed the use of the infiltration family concept as a way of categorizing infiltration behavior for different soils (USDA-SCS, 1974; USDA-SCS, 1984). The corresponding infiltration equation is given by Eq. (4), in which *k* and *a* are specific to each family but *c* is constant for all families. Because of the similarity between the infiltration families presented in the 1974 and 1984 publications, WinSRFR combines those families as a single set. While a new set of NRCS infiltration families has been recently proposed (Walker et al 2006), those families have not been adopted for the current release of the program but may be adopted in a future release. The characteristic-time concept is based on the premise that infiltration can be characterized by the time needed to infiltrate the target depth. When using this concept, the *characteristic* time, target depth, and an exponent for Eq. (1) (gleaned from previous experience with soils in the area) need to be specified; the parameter *k* can be found then from Eq. (1). The Merriam and Clemmens' (1985) Time-Rated families are based on the same concept, but enhanced by an empirical study that related the time to infiltrate a target depth of 100mm, $\ddot{A}_{100}$, to the exponent *a*. The relationship is presented as Eq. (5), in which $\ddot{A}_{100}$ is expressed in hours. The branch function (Clemmens, 1981) models a discontinuous infiltration rate, in which steady-state is achieved suddenly following an initial period in which infiltrate rate changes rapidly. In Eq. (5), $\ddot{A}_b$ is the time the function branches to the constant final infiltration rate, *b*.

Empirical infiltration equations have a long history of use in surface irrigation engineering analyses because they tend to fit reasonably well field-measured data. Moreover, simulation studies have shown that the behavior of different empirical equations is consistent with solutions developed from porous media flow theory (Haverkamp et al., 1988; Perea et al. 2003; Furman et al., 2006). Hence, selection of a function for a particular use does not depend on theoretical considerations but, rather, on its ability to represent the measured infiltration behavior for a time commensurate with the duration of particular irrigation event. For example, with lengthy irrigation events in which the infiltration rate approaches a steady state, one would use a formulation containing the *b* term.

Infiltration Function

Advance & Recession
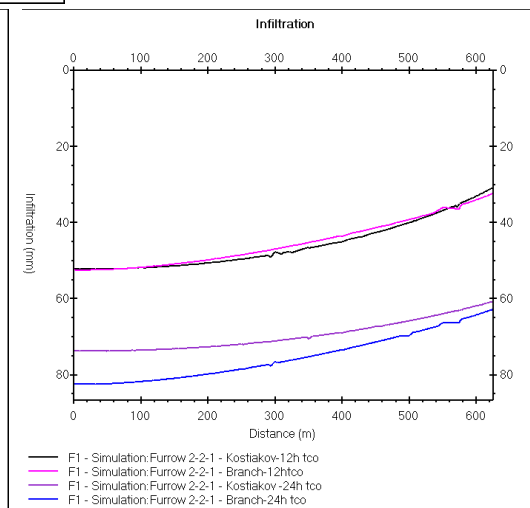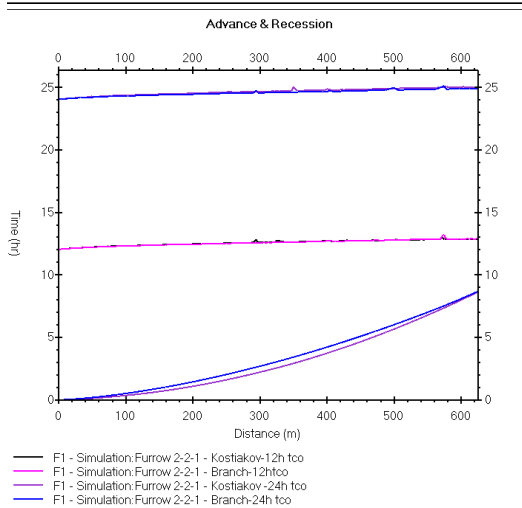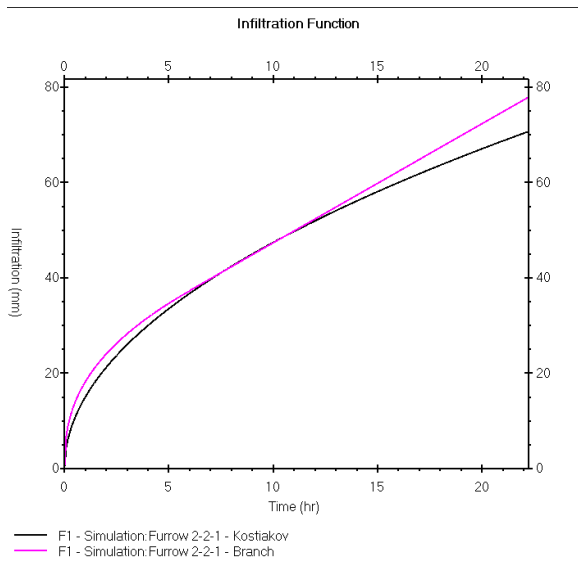
Infiltration

Wetted perimeter effect options
WinSRFR offers four wetted perimeter choices when dealing with furrows, each of which represents a different assumption for the effect of variable flow depth on infiltration. The choice of *WP* option depends partly on user preference but also on the method adopted for calculating *z*. The relationship between *z* and *WP* will be explained later.

Furrow spacing. This simple assumption uses the furrow spacing *FS* as a nominal wetted perimeter. Then,

$$A_z = WP \cdot z = FS \cdot z \qquad\qquad (7)$$

and the dimensions of *z* are volume/unit length/*furrow spacing*. This formulation is equivalent to the approach used in other furrow-irrigation models (e.g., SIRMOD - Walker, 2003) and in the 2006 NRCS infiltration families (Walker et al., 2006) which input a formula for furrow infiltration A_z (volume per unit length) directly, rather than for *z*, i.e.,

$$A_z = K\tau_x^a + B\tau_x + C \tag{8}$$

In this expression the units of K, B, and C reflect the area units of A_z. For a given irrigation scenario, if infiltration function is specified in the form of Eq. (8), the parameter values can be converted to a form compatible with Eq. (1) (i.e. from uppercase to lowercase parameter values) simply by dividing by the furrow spacing.

NRCS empirical wetted perimeter. The NRCS infiltration families were originally developed from data collected in border irrigation trials (with dimensions of volume/unit length/*unit width*). The agency developed a procedure to adapt the resultant one dimensional-infiltration families to infiltration in furrows through an empirical wetted perimeter WP_{NRCS} (USDA-SCS, 1984; Walker et al., 2006). This is calculated for the flow conditions (discharge Q, bottom slope S_0, and Manning roughness n) at the inlet end of the furrow but applied to the entire length of the irrigation stream. Then,

$$A_z = WP_{NRCS} \cdot z_{NRCS} \tag{9}$$

in which z_{NRCS} is given by Eq. (3). The formula for WP_{NRCS} is

$$WP_{NRCS} = c_1 (Q\,n / S_0^{0.5})^{0.4247} + c_2 \tag{10}$$

in which c_1 and c_2 are constants that depend on the units of Q and WP_{NRCS} (if Q is given in l/s and WP_{NRCS} in m, the constants are 0.265 and 0.227, respectively). WinSRFR interprets Q as the average discharge rate over the total period of inflow, except in cut-back scenarios in which -- like in the original USDA-SCS publication -- before- and after-cutback values are inserted in the formula -- with consequent reductions in wetted perimeter after cutback. Likewise, the bottom slope that WinSRFR enters in the formula is the average bottom slope for the entire length of run. For zero slope cases, S_0 is replaced with the following estimate of the friction slope S_f (USDA-SCS, 1984):

$$S_f = \frac{c_3\,Q^{c_4}}{L} \tag{11}$$

In Eq. (11), $c_4 = 0.3419$ and c_3 is a constant dependent on the units of Q and L (0.9282 m/ (m^3/s) ^{c4}). The numerator of Eq. (11) is an empirical encapsulation of data on the flow depth at the furrow inlet, while L is the total furrow length.

A key feature of Eq. (10) is that the constant c_2 accounts for two distinct physical factors. One, amounting to 0.01408 m, is part of the fit of the formula to many different combinations of trapezoidal-furrow base and side slopes. The larger part, 0.213 m, reflects the observation that lateral and even upward suction in a furrow increases its infiltration over what would occur downward in a border strip of width equal to the furrow's wetted perimeter. The 0.213 m constant represents an approximate, empirical fit to the data (see Strelkoff and Clemmens, 2007, for a comparison of the formula's results with wetted perimeter based solely on the geometry of trapezoidal furrows).

Equation (10) was developed based on trapezoidal furrows with bottom widths between 0.06 and 0.15 m and side slopes (H/V) between 1:1 and 2:1 (USDA-SCS 1984) and should not be used outside this range. Even within this range, wetted perimeter can vary substantially while Eq. (10) computes the same value for any combination of bottom width and side slope (Perea et al., 2003). Similarly, Eq. (11) ignores the effect of furrow geometry, and additionally of hydraulic roughness, on the hydraulic gradient. The range of application of this formula is not stated in the original USDA-SCS publication. Finally, use of Eq. (10) in combination with Eq. (11) results in a small discontinuity in the calculated wetted perimeter, when going from small slopes to a zero slope. Despite these limitations, these procedures were incorporated into the WinSRFR package because they are supported by field-measured data and continue to be used by NRCS personnel in combination with the infiltration families.

Representative upstream wetted perimeter.   Two of the wetted perimeter options offered by the original SRFR engine were Upstream Wetted Perimeter at Normal Depth and Upstream Wetted Perimeter. The former option is applicable with relatively steep bottom slopes, i.e. under conditions where kinematic flow conditions can be assumed (Strelkoff and Clemmens 1994). The latter option applies also to fields with relatively mild slope, in which upstream rises gradually. With both options, the SRFR engine updates the wetted perimeter as a function of time-variable flow $Q(t)$. These same options were incorporated into WinSRFR V1.1. The Representative Upstream Wetted Perimeter replaces those options. It is conceptually similar to the USDA-NRCS approach in that it assumes a constant wetted perimeter effect based on the average inflow to the furrow and the average field slope, but does not include any term to account for lateral infiltration. The expected dimensions of z are, as with Eq. (9), volume/unit length/unit width. The method calculates the upstream flow depth y_0, which is needed to calculate the representative upstream wetted perimeter, using the following relationship (Bautista et al., 2008)

$$-\frac{\beta y_0}{L} = S_0 - \frac{Q^2 n^2}{A^2 R^{4/3}} \qquad (12)$$

Eq. (12) is an approximation to the zero-inertia equation of unsteady open-channel flow (Strelkoff and Clemmens, 2007),

$$\frac{\partial y}{\partial x} = S_0 - S_f \qquad (13)$$

In these expressions, L is the field length, and β is a correction factor intended to account for the curvature of the water-surface profile. A value of β of 0.45 gives reasonable upstream depth estimates under a wide range of flow conditions, except with steep slopes and short irrigation times (Bautista et al., 2008). Established geometric relationships for both trapezoidal and parabolic (power-law) furrows are used to determine A, WP, and therefore, R, the hydraulic radius. Calculations for parabolic furrows are based on the procedures described in Strelkoff and Clemmens (2000), which also points out the inconsistency in the common practice of specifying both top width and wetted perimeter as monomial power laws of depth.   Eq. (12) can be applied with any non-negative value of S_0 and yields normal depth for sufficiently large values of S_0 and L. The expression was initially developed to estimate y_0 at any time during the advance phase. In that case, the average Q is substituted with the instantaneous Q and L with the stream advance distance x_A.

Local wetted perimeter. In the only option that takes the unsteady rise and fall of local furrow depths into account, the Simulation World uses Eq. (14) to compute the increment A_Z in the course of a time step at a particular location x_i and time t_j as the product of the increment in z (volume/unit length/unit width) and the current wetted perimeter, averaged over the time step.

$$A_{i,j} = A_{i,j-1} + \delta A_{zi,j} = A_{i,j-1} + \{z(\tau_{i,j}) - z(\tau_{i,j-1})\} * \overline{WP}_{i,j} + c(WP_{i,j} - WP_{i,j-1}) \qquad (14)$$

Here, $\overline{WP}_{i,j}$ is the average wetted perimeter over the time step computed as a geometrical function of flow depth at that location and time, and the constant c term contributes to A_Z only if $WP_{ij} > WP_{i,\,j-1}$. Use of this formula is presently limited because the parameters cannot be readily estimated by conventional volume-balance procedures, including those currently provided by WinSRFR.

Relationship between infiltration function and wetted perimeter
The *z-WP* combinations allowed by WinSRFR are listed in Table 2. Use of the empirical NRCS wetted perimeter is allowed only in combination with the NRCS Infiltration Families, since those concepts were developed jointly. Similar to the NRCS Families, the Time Rated families have published coefficients and the resulting *z* values have dimensions of volume/ unit width/ unit length. They were developed for border irrigation, but can be adapted to furrows only if adjusted on the basis of wetted perimeter, either using the representative or local wetted perimeter concepts. Because the coefficients of the Kostiakov, Modified Kostiakov, Characteristic Time, and Branch equations are calibrated values, they can be used in combination with any of the wetted perimeter options, except the NRCS option. This does not make the wetted perimeter option interchangeable because the coefficients of *z* are specific to a particular wetted perimeter option.

Table 2. *z-WP* combinations allowed by WinSRFR for the computation of infiltration per volume length in furrows.

Infiltration formula	Furrow wetted perimeter options
• Kostiakov • Modified Kostiakov • Branch	• Furrow spacing • Representative upstream wetted perimeter • Local wetted perimeter
• NRCS infiltration families	• NRCS empirical wetted perimeter
• Time-Rated infiltration families	• Representative upstream wetted perimeter • Local wetted perimeter
• Characteristic Time	• Furrow spacing

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5.2   Surface Irrigation Design

WinSRFR Adjustments for Surface Irrigation Design

By A.J. Clemmens[1] E. Bautista, J.L. Schlegel

Abstract

The movement of water over the soil surface under surface irrigation has been studied extensively over the last century. However, irrigators are still faced with significant challenges in making surface irrigation systems efficient. In the past, each surface irrigation method was treated differently because of differences in the simplicity with which different phases of the irrigation could be described. This has tended to make surface irrigation analysis and design appear disjointed. In this paper, the same basic procedures are applied to the design of various surface systems, deviating where needed to make the procedures both straightforward and sufficiently accurate. The basis for these designs is the ability to predict advance, recession, the distribution of infiltrated water, and the performance for a given set of conditions. Conservation of mass is the main concept, with empirical approximations used where needed. This paper presents the relevant equations. A companion paper provides solution procedures for hand calculation and discussion of how to apply these in a design setting. Spreadsheets to perform these calculations are available on the Sakia ejournal web site http://ejlw.sakia.org/.

Keywords: surface irrigation, design, management, application efficiency, irrigation performance

1 Introduction

Many surface irrigation systems are ineffective and inefficient. This can be caused by physical constraints (e.g., steep land slopes, shallow soils, poor water supplies, etc.), by poor design and layout, or by improper operation and management. A thorough discussion of the constraints and limitations of surface irrigation systems is beyond the scope of this paper. For more details, see Walker and Skogerboe (1987), Clemmens and Dedrick (1994), or Burt et al. (2000). One advantage of surface irrigation over pressurized irrigation methods is that it often does not require a good, reliable water supply. It can be adapted to different rates of flow, flows that vary randomly, and flows with poor water quality (sediment, debris, etc.). Efforts in surface irrigation research and extension have focused on methods for providing better water control -- control over flow rate or control over volume applied. These generally focus on how the system is operated. Of equal importance is field design and layout. Good operation cannot make up for a poor field design. However, when surface irrigation systems are properly designed and more modern operating procedures are used, irrigation efficiencies and uniformities can be high (Kennedy, 1994, p 166).

Surface irrigation methods can be categorized according to how they function hydraulically. Distinctions can be made by advance and recession curves, which describe the time when the advancing stream reaches particular locations and the time when standing water no longer occurs there. This hydraulic comparison assumes that water enters the field or irrigation set along one end and flows to the other end uniformly across the set width. The following categories of surface irrigation are considered: sloping furrows, border strips, level basin, and level furrows (Table 1). The main differences in hydraulic performance among these categories are related to the magnitude and pattern of the inflow rate, the general shape of the recession curves, and runoff hydrographs. Unfortunately, past methods for design have used widely different approaches and assumptions, making the design process somewhat confusing.

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The purpose of this paper is to present simple, consistent calculation procedures that can be used in the design of *modern* surface irrigation systems, which can be easily calculated and implemented in a spreadsheet. Here, *modern* implies a reasonable control over the water supply. Design of rice paddies and methods such as contour levee, contour ditch, wild flooding, etc. are not discussed. The equations and calculation procedures are based on continuity, but include some empirical expressions for convenience. These calculations are used to determine advance and application times and the resulting distribution of infiltrated water for a specific set of conditions. Design requires a trial and error process to determine appropriate field dimensions and operational recommendations. The examples in the companion paper lay the groundwork for extending these simple equations to design.

2 Design Considerations

2.1 Design Objectives

The amount of water to be supplied during an irrigation event, referred to as the target or required depth of application, is a major design consideration. Surface irrigation systems have a narrow range of target depths for which they are reasonably efficient and uniform. The irrigator must adjust irrigation practices (typically flow rate and application time) to account for changing field conditions (infiltration and roughness). Irrigators often develop rules of operation that they use to make adjustments. A poor field design will make these judgments difficult for the operator. A good design will provide guidance on system operation.

Surface irrigation systems are most applicable on mild to level slopes. On steeper slopes, erosion can become excessive and the range of operating conditions can be narrow (e.g., narrow range of target depths).

The design objectives are typically stated in terms of achieving some desired application efficiency, *AE*. This efficiency is called potential application efficiency, *PAE*, here to distinguish it from a field measured *AE*. Design is typically based on supplying the target depth of water everywhere in the field. The PAE_{min} is the application efficiency when the minimum depth infiltrated just equals the target depth.

$$PAE_{min} = \frac{d_{min}}{d_a} = \frac{d_{req}}{d_a} \quad \text{(1)}$$

where d_{req} is the required depth, d_{min} is the minimum infiltrated depth, and d_a is the depth of applied irrigation water, in this case, the depth applied that results in the minimum depth just equal to the required depth. In practice, some underirrigation is usually allowed and operation is based on satisfying the low-quarter depth. Since design does not take into account all of the variability which exists within the field, design is based herein on satisfying the minimum depth, with the expectation that when operated the low quarter depth would be satisfied.

Surface irrigation design requires the estimation of parameters that define the infiltration of water into the soil and the resistance to water movement caused by the soil surface and vegetation. These are key factors in the design.

2.2 Equations for Flow Resistance

Resistance to flow is usually described by the Manning equation, which relates flow rate, Q, to the flow area, A, hydraulic radius, R (area over wetted perimeter), friction slope, S_f, and Manning roughness coefficient, n. A units coefficient, C_u, is required to make this dimensionally homogeneous, where $C_u = 1\ \text{m}^{1/2}/\text{s}$.

$$Q = \frac{A\, R^{2/3}\, S_f^{1/2}}{n / C_u} \qquad (2)$$

The base units in Equation 2 are meters and seconds.

2.3 Equations for Infiltration

Infiltration is one of the most important factors affecting the design and performance of surface irrigation systems. Unfortunately, estimating infiltration conditions is one of the most difficult things to do in the field. Irrigation engineers have tended to use the Kostiakov Equation, or a variation thereof, defined by

$$d(\tau) = k\,\tau^a \qquad i(\tau) = ak\,\tau^{a-1} \qquad (4)$$

or in modified form

$$d(\tau) = c + k\,\tau^a + b\tau \qquad i(\tau) = ak\,\tau^{a-1} + b \qquad (5)$$

where d is the infiltrated depth; i is the infiltration rate; τ is the infiltration opportunity time; and a, b, c, and k are empirical coefficients.

An alternative to the Modified Kostiakov equation is the Kostiakov branch function. The first branch uses Equation 5 (with $b=0$) for short times, and switches to a constant infiltration rate when the infiltration rate equals b. For soils that reach a nearly constant, final infiltration rate during the irrigation, design and evaluation can be greatly simplified with use of this equation. The Kostiakov branch function equations are

$$
\begin{aligned}
d(\tau) &= c + k\,\tau^a & i(\tau) &= ak\,\tau^{a-1} & \text{for } \tau &\leq \tau_B \\
&= c_2 + b\tau & &= b & \text{for } \tau &\geq \tau_B
\end{aligned}
\qquad (6)
$$

where τ_B is the time when the infiltration rates for the two branches match.

Infiltration in furrows can be significantly more complicated than in flat borders or basins due to the two-dimensional nature of the furrow cross section. Infiltration in borders and basins is generally considered to be one dimensional — downward. Infiltration in furrows can be influenced by the wetted width of the stream and lateral flow into the furrow bed. For design, it is generally sufficient to express infiltration as infiltrated volume per unit length per unit width. Then, calculated infiltration is not influenced by actual differences in wetted width over the length of run. Infiltration could be expressed as a function of furrow spacing, the wetted width at the upstream end under normal depth, or some related depth. Then, for example, infiltration could change with inflow rate. Further discussion is beyond the scope of this paper.

3 Design Approach

3.1 Opportunity Time Criteria

The amount of water to be supplied during an irrigation event, referred to as the target or required depth of application, d_{req}, is a major design consideration. Surface irrigation systems have a narrow range of target depths for which they are reasonably efficient and uniform. Design approaches are often based on assuming that one end of the field or the other will receive the least infiltrated depth. Then, the inflow and application time are adjusted such that the required depth is infiltrated at that location. The time to infiltrate the required depth, τ_{req}, becomes an important design parameter. Typically, it has more influence on the design than the constants in an infiltration formula themselves.

The infiltration opportunity time at any location, x, along the length-of-run, $\tau_{opp}(x)$, is defined as the time between advance, $t_A(x)$, and recession, $t_R(x)$ or

$$\tau_{opp}(x) = t_R(x) - t_A(x) \quad \text{(7)}$$

At the head end of the field ($x = 0$), the opportunity time is equal to the recession time, or

$$\tau_{opp}(0) = t_R(0) = t_{co} + t_{lag} \quad \text{(8)}$$

where t_{co} is the time of cutoff or application time and t_{lag} is the recession lag time, or the time required for the water depth at the upstream end to drop to zero after cutoff (Figure 1). Design based on meeting the requirement at the upstream end does not require advance and recession curves to be computed. However, an estimate of PAE_{min} is required, along with a method for estimating recession lag time (USDA, 1974). For short border-strips and steep slopes, the minimum depth infiltrated can be at the head end of the strip. However, numerous runs with the BORDER design program (Strelkoff et al. 1996) indicated that for most situations near the highest potential efficiency, the minimum depth was at the downstream end. Even when the minimum was at the upstream end, the extent of low quarter depths was split between the upper and lower ends. Thus design based on the downstream end should give more consistent results over the range of typical design conditions. Design based on satisfying the requirement at the upstream end is no longer recommended, except under ponded conditions, discussed later.

With the minimum depth at the downstream end of the field, furthest from the water source ($x = L$), advance and recession curves must be computed. Estimating the appropriate inflow rate and time required to achieve τ_{req} at the downstream end is more difficult. Specifically (Figure 1),

$$t_R(L) = t_A(L) + \tau_{req} \quad \text{(9)}$$

Precise solutions of advance and recession are possible with solution of the Saint Venant equations of continuity and momentum. However, this approach requires a numerical solution, done on a case by case basis. It does not directly produce general equations for advance and recession. The time of cutoff that will produce the target depth at the downstream end is

$$t_{co} = t_A(L) + \tau_{req} - [\, t_R(L) - t_R(0) + t_{lag} \,] \quad \text{(10)}$$

where the term in brackets is the time between cutoff and recession at the downstream end (Figure 1). A more or less uniform approach can be used for computing advance curves for the various surface irrigation methods. Recession curves are more difficult to estimate and thus different approaches are used to solve the last term in Equation 10 for the different methods. These approaches range from assuming the term can be neglected, to the use of empirical equations. In this paper, calculation procedures are provided for advance, cutoff time, recession, infiltrated water distribution, and runoff volume that will satisfy the minimum depth at the downstream end, which can subsequently be used in the design process.

3.2 Assumed-Surface Volume Method for Advance

All design methods must use procedures that satisfy a volume balance, regardless of how sophisticated they are. In this paper, assumptions are made regarding the surface volume in order to use a volume balance to determine an advance curve. This has advantages over strictly empirical equations since the assumptions regarding the surface volume can be verified with field observations or from computer simulation.

During advance, the cumulative infiltrated volume at any time is equal to the difference between the accumulated inflow volume and the surface storage volume. This volume balance relationship may be expressed as:

$$V_{in}(t) = V_y(t) + V_z(t) \qquad \textbf{(11)}$$

where $V_{in}(t)$ is the inflow volume at time t, $V_y(t)$ is the volume in surface storage at time t, and $V_z(t)$ is the infiltrated volume at time t. Using this relationship to determine advance time, t, to distance x requires calculation of surface and subsurface volumes. Typically, Equation 11 is put in the following form

$$Q_{in} t_x = \phi_0 \, \sigma_y \, A_0(t_x) x + \sigma_z W z(t_x) x \qquad \textbf{(12)}$$

where $A_o(t)$ is the cross-sectional flow area at the inlet at time t, $\tilde{A}_y$ is the surface storage shape factor, W is the width, $\tilde{A}_z$ is the subsurface shape factor (all units are in meters and seconds), and $\tilde{A}_0$ is an adjustment parameter, discussed below. The surface shape factor is the ratio between the average cross-sectional flow area and that at the head of the field, also discussed below.

The subsurface shape factor is the ratio between the average infiltrated cross-sectional area (infiltrated depth times width), and the infiltrated cross-sectional area (depth times width) at the head of the field. When infiltration is defined by Equation 5 or 6, the subsurface shape factor in Equation 12 is difficult to determine. It is easier to rewrite the subsurface volume in the following form (adapted from ASAE 1991)

$$V_z = W(c + \sigma_{z1} \, k \, t_x^a + \frac{h}{1+h} b \, t_x) x \qquad \textbf{(13)}$$

where h is the exponent in the advance equation

$$t = s \, x^h \qquad \textbf{(14)}$$

where s is a constant. Then $\tilde{A}_{z1}$ can be found from (ASAE 1991)

$$\sigma_{z1} = \frac{h + a(h-1) + 1}{(1+a)(1+h)}$$ **(15)**

Determining an advance curve requires knowledge of Q_{in}, A_0, $\tilde{A}_y$, the infiltration constants (c, k, a, and b), and the width. Defining this curve is an iterative process since the advance exponent h and advance times are interrelated and must be solved for simultaneously.

A common approach has been to use the advance time at two locations to determine the advance exponent in Equation 14, typically the field length and ½ the field length. From these two time-distance pairs, the advance exponent can be computed from

$$h = \frac{\log(t_{L/2}/t_L)}{\log(1/2)}$$ **(16)**

If the above system of equations are applied for a given situation (with inflow rate, length, width, infiltration and roughness known) at these two advance time-distance pairs, with Equation 13 replacing the second term in the right hand side of Equation 12, there are eight unknowns; $\tilde{A}_y$, $A_0(t_L)$, $A_0(t_{L/2})$, $\tilde{A}_{z1}$, t_L, $t_{L/2}$, h, and s, with five equations; Equations 12 and 14 at two distances, and Equation 15. Solution of these equations requires external estimates of $\tilde{A}_y$, $A_0(t_L)$, and $A_0(t_{L/2})$. The main problem is that the A_0 and $\tilde{A}_y$ are not known in general. For steep slopes, the surface volume is typically a small fraction of the total inflow volume, such that rough estimates of these parameters give reasonable advance predictions; where typically, A_0 is assumed equal to the flow area at normal depth and $\tilde{A}_y$ is given a value of 0.7. For milder slopes, the surface volume is often a large portion of the inflow volume, even at the time of cutoff. Also, A_0 changes continuously during the irrigation event, and in some cases never reaches normal depth. Similarly, $\tilde{A}_y$ can vary.

In WinSRFR, we use the zero-inertia representative depth determined from:

$$S_f - S_0 = \frac{y_0}{L}$$

which is solved for the upstream depth y_0, with S_f computed as in equation (2) and S_0 = bottom slope. For steep slopes, the depth is approximately normal depth. For milder slopes, the depth can be much smaller than normal depth. This representative depth is computed at both L and L/2 for computing $A_0(t_L)$ and $A_0(t_{L/2})$ and thus advance.

Monserrat and Barragan (1998) suggest the use of unsteady-flow simulation results to determine values for the average surface water area, $\tilde{A}_y A_0$. **Here, we use simulation results directly for a single calibration point (e.g., for a given length and either width of flow rate) and then apply the calibration results to the remaining points. The adjustment parameter A_0 is used to make the advance time computed with equation (12) match the advance time from WinSRFR simulation. This adjusts for differences in $\tilde{A}_y$, $A_0(t_L)$, and $A_0(t_{L/2})$. The same advance matching procedures is used for all methods.**

3.3 Performance

The potential application efficiency is computed as the required volume (required depth times furrow spacing times furrow length) divided by the applied volume (inflow rate times cutoff time). No adjustment is needed for under irrigation since this approach assumes the entire field is adequately irrigated. The volume of runoff can be estimated by computing a distribution of infiltrated depths (based on recession minus advance times), the associated infiltrated volume, and subtracting this volume from the inflow volume. Better estimates of these volumes can be made by computing advance, recession, and infiltration at a series of points, i.e. numerical integration. Eight points has proven to be satisfactory in most cases. The deep percolation volume is the infiltrated volume minus the required volume, since it is assumed that all points receive at least the required depth.

The following procedures assume that length, slope, and inflow rate are known. The procedure then determines the minimum application or inflow time required to meet or exceed the required depth everywhere. This provides an estimate of PAE_{min}. Design for a specific set of field conditions (i.e., infiltration, roughness, and required infiltration depth) requires repeated application of these procedures to determine an appropriate furrow length, slope, and inflow rate by trial and error. More systematic application of these relationships is discussed in a companion paper.

4 Sloping Furrow Irrigation

4.1 Assumptions

With sloping furrow irrigation, water advance must be sufficiently fast so that the downstream end will receive adequate water while the upstream end is not excessively over irrigated. However advance that is too rapid can result in a large percentage of the applied water running off the field, unless inflow after completion of advance is reduced, for example with a cutback, surge, or cablegation system, or the runoff is collected for reuse.

Furrow slopes in areas of high rainfall should be great enough to allow adequate drainage ($> 0.03\%$), yet not so great as to cause significant erosion. The following guidelines are taken from USDA (1984). For erodible soils (e.g., silty soils), the maximum furrow slope should be limited to $60/(P_{30})^{1.3}$, where P_{30} is the 30-minute rainfall in mm for a 2-year frequency. This limit can be exceeded by about 25% for less erodible soils (e.g., sandy and clayey soils). Further, erosion can be limited by placing a limit on the irrigation stream size. The maximum flow velocity should be limited to 8 and 13 m/min for erodible and non-erodible soils, respectively. The relationship between velocity and flow rate can be obtained from Equation 2, since velocity is flow rate, Q, divided by flow area, A.

The furrow cross-sectional area and wetted perimeter must be specified as a function of flow depth (i.e., normal depth). Any function can be useful provided that it properly describes the cross section. Trapezoidal and power-function shapes are commonly used. Then the normal depth for a given discharge can be found by trial and error from Equation 2.

This design approach assumes that the wetted width does not vary over the length of the furrow. That is, the infiltrated volume over a unit length of furrow is dependent only on the infiltration opportunity time and not on the depth of flow or wetted width. For heavy soils with significant lateral sorption, the wetted width from adjacent furrows overlap, making the wetted width per furrow essentially equal to the furrow spacing. For coarse textured soils, a significant reduction in infiltration along the furrow can result from the reduction in wetted width due to a reduction in flow depth as the flow rate gets smaller with distance from the head end. For this latter

case, field design should not attempt to minimize runoff since this would drastically reduce furrow flow rates toward the downstream end. Other measures (e.g., return flow) are needed to improve performance in these cases.

4.2 Advance

Discussed above.

4.3   Recession

An adjustment to the recession curve is made by subtracting a fraction of the volume of water on the surface at the time of cutoff from the total applied volume. Then the application time is found from

$$t_{co} = t_A(L) + \tau_{req} - \phi_1 \left(\frac{V_y(L)}{Q_{in}} \right)$$ (17)

where ϕ_1 is an adjustment amount to provide the correct t_{co} that gives the design recession time at the downstream end (advance time plus τ_{req}) from simulation.

The recession time at the upstream end is computed as the cutoff time, t_{co}, plus a fraction of the recession lag time from Strelkoff (1977)

$$t_R(0) = t_{co} + \phi_2 \left(\frac{A_0(t_{co})L}{2Q_{in}} \right)$$ (17b)

where ϕ_2 is an adjustment that provides the correct infiltrated and runoff volumes, assuming a straight line recession curve.

Figure 2 shows advance and recession curves generated with the above equations without adjustment ($\phi_1 = 1$, $\phi_2 = 0$, $\phi_3 = 0$) and from simulation with SRFR (Strelkoff et al. 1990). Specifics include $L = 400$m, $S_0 = 0.002$, $k = 30.1$ mm/hr^a, $a = 0.35$, $n = 0.05$, $d_{req} = 80$ mm, furrow spacing = 1 m, $Q_f = 1.0$ l/s, and trapezoidal furrow shape with bottom width = 100 mm and side slopes = 2:1, horizontal to vertical. Clearly the adjustment to the recession time from Equation 17 is reasonable in this case.

4.4 Sloping Furrows with Cutback

The efficiency of furrow irrigation systems can often be improved by reducing the inflow rate after water has advanced to the end of the field. A high initial flow rate can provide rapid advance, and thus more uniform opportunity time, while cutting back the stream will reduce the amount of runoff. If the cutback stream is too small to keep up with infiltration, recession can occur at the downstream end and move back up the field. Rather than cutting off at the completion of advance, cutoff is typically delayed until infiltration is somewhat reduced. This will also help assure that the downstream end receives sufficient flow depth and wetted perimeter.

A common practice is to cut back to 50% of the inflow. Dividing the cutback inflow rate by the wetted field area gives the average infiltration rate that matches the cutback inflow

$$\bar{i}_{CB} \leq \frac{Q_{CB}}{WL} \qquad \textbf{(18)}$$

The average infiltration rate at any time after completion of advance can be computed from numerical integration over the distance (e.g., the 8 intervals used above). A direct analytical solution for average infiltration rate is not possible, but a numerical approximation can be found by integrating infiltration rate over distance. Infiltration at any point and any time is a function of the infiltration time, or the current time minus advance time. The advance time is a function of x^h, from Equation 14. If this term is replaced with a truncated series expansion, with higher order terms removed (i.e. $x^h = 1 + h(x\text{-}1)$), an analytical expression for the infiltration rate, averaged over the field length, can be found, namely

$$\bar{i}_{CB} \approx b + \frac{akt_{CB}^{(a-1)}}{ah}\left[\left(\left\{\frac{t_{CB}}{t_L}\right\} - 1 + h\right)^a - \left(\left\{\frac{t_{CB}}{t_L}\right\} - 1\right)^a\right] \qquad \textbf{(19)}$$

where t_{CB} is the time of cutback. The cutback time to achieve the necessary average infiltration rate can be determined from Equation 19 by trial and error.

This is a very conservative estimate of cutback time since the reduction in flow results in less surface storage on the field, and this change in surface storage can contribute to infiltration. A conservative estimate of the correction in cutoff time can be found by dividing the change in surface volume by the cutback flow rate, which is related to the distance averaged infiltration rate through Equation 18. The adjusted cutback time is simply

$$t_{CBadj} = t_{CB} - \frac{V_y(Q_{in}) - V_y(Q_{CB})}{Q_{CB}} \qquad \textbf{(20)}$$

where the surface volume after completion of advance is now a function only of flow rate.

The cutoff time is computed according to Equation 17, but with $V_y(t_{co})$ replaced with $V_y(Q_{CB})$ and Q_{in} replaced with Q_{CB}. The cutoff time is actually slightly longer, since the ratio of volume to flow rate (last term in Equation 17) is larger. For some soils, the reduction in wetted perimeter caused by cutback might require an increase in total application time. **The adjustment procedures developed from WinSRFR are the same as used for furrows without cutback, except that the cutback flow rate and associated surface volume are used to adjust A_1 and A_2 equations 17 and 17b.**

4.5 Sloping Furrows with Runoff Reuse

Not included in WinSRFR.

4.6 Level Furrows

WinSRFR uses the same procedure for both sloping and level furrows.

5 Border-Strip Irrigation

5.1 Assumptions

With border-strip irrigation, flow resistance from vegetation causes a significant amount of water to be in surface storage. For efficient irrigation, this often requires that the inflow be cut off prior to the completion of advance. The recession in border strips is also much slower than furrows due to the vegetative resistance and the geometry. If resistance changes substantially during the growing of a crop, different flow rates are often required to maintain efficient irrigation over the season. Thus design needs to provide a layout such that inflow rate and time can be adjusted within reason to provide satisfactory performance.

The Soil Conservation Service (USDA 1974) provided the following recommendations. The maximum recommended inflow rate to limit erosion on non-sod forming crops, such as alfalfa and small grain is found from

$$q_{in_{max}} = 0.00018 S_0^{-0.75} \qquad (27)$$

where S_0 is in m/m and q_{in} is in m^2/s. For sod forming crops, twice this value can be used. A minimum inflow rate has also been suggested so that the water depth will be sufficient to spread laterally

$$q_{in_{min}} = \frac{0.000006 \, L \, S_0^{1/2}}{n} \qquad (28)$$

Border-strip irrigation is typically practiced on slopes less than 0.05 m/m (5%). On fine textured soils, slopes are typically less than 0.01 m/m. The maximum slope based on the criteria for minimum flow depth (and discharge) can be found by solving Equation 28 for S_0. This does not consider erosion potential.

5.2 Open-Ended Border Strips

For sloping borders, recession can not be assumed to start at cutoff. For design, the recession time at the downstream end is set so that the required depth is just satisfied there, as in Equation 10. An empirical relationship, adapted from Walker and Skogerboe (1987), can be used to estimate the cutoff time for this required downstream recession time. An approximate upstream recession time is found from

$$t_{co} = t_R(L) - \frac{y_o L}{2q_{in}} - \phi_1 \frac{0.666 n^{0.47565} S_y^{0.20735} L^{0.6829}}{I^{0.52435} S_0^{0.237825}} \qquad (30)$$

where all units are in meters and seconds and S_y is

$$S_y = \frac{1}{L} \left[\frac{(q_{in} - IL)n}{S_0^{0.5}} \right]^{0.6} \qquad (31)$$

and I is the infiltration rate (m/s) at $t_R(0)_S$, averaged over the length. For the branch infiltration function after the branch point, it is simply b. For the other infiltration functions, the infiltration rate can be numerically integrated or approximated by averaging the values at the upstream and downstream ends, $\ddot{A}(0) = t_R(0)_S$ and $\ddot{A}$ (L) = $t_R(L) - t_A(L)$. Equation 30 is essentially an empirical fit to a series of computer runs over a wide variety of conditions. It is based on an estimate of the upstream recession lag time from (Strelkoff, 1977). **The parameter A_1 is an adjustment such that the value of t_{co} provides the correct infiltration opportunity time at the downstream end.**

Solution of Equations 30 and 31 for $t_R(0)_S$ is essentially a trial and error process if the average infiltration rate is not fixed (i.e., with the Kostiakov branch function, the trial and error is not needed).

While the recession time within Equation 30 is needed for the procedure used to compute cutoff time, it does not give a very realistic estimate for the actual upstream recession time for border strips on small slopes. The following equation can be used to estimate the upstream recession time (adapted from Hart et al. 1980).

$$t_R(0) = t_{co} + \phi_2 \frac{q_{in}^{0.2} n^{1.2}}{[\, S_0 + (\frac{0.345 n q_{in}^{0.175}}{\tau_{req}^{0.88} S_0^{1/2}})\,]^{1.6}} \tag{33}$$

where units are in meters and seconds. **The parameter A_2 is adjusted based on simulation to give the correct infiltration opportunity time at the upstream end.** The recession lag times for steeper slopes are generally very small and either equation gives reasonable results. For smaller slopes (e.g. < 0.004), Equation 33 generally gives the best estimate (i.e., it is recommended over Equation 30). The procedure given above for computing cutoff times appears to be valid over a wide range of slopes even if it gives poor estimates of recession lag time.

The above procedure estimates the two ends of the recession curve. For steeper slopes, a straight line through two points can give reasonable results. For milder slopes, a straight line generally underestimates the volume infiltrated and overestimates the volume of runoff. **To match WinSRFR simulation, we must match the correct infiltrated volume. In WinSRFR,** the downstream part of the recession curve is assumed horizontal and the upstream part of the recession curve is computed from

$$\frac{d\,t_R}{dx} = \max \,[\, \frac{\phi_3 \, \sigma_y \, y_n}{q_{in}} , \frac{t_R(L) - t_R(0)}{L} \,] \tag{34}$$

with the restriction that the computed recession time at any distance not exceed the recession time at the downstream end. The second term in the brackets of Equation 34 is just a straight line between the recession times; $t_R(L)$ computed from Equation 9 and $t_R(0)$ computed from Equation 33. The first term assumes that recession progresses at a rate which removes the surface volume, linearly, at **a fraction** of the inflow rate – a strictly empirical estimate.

Figure 3 shows an example of advance and recession curves with simulation and from the procedures discussed above ($_0 = 1$, $_1 = 1$, $_2 = 1$, $_3 = 3$). Specifics include $L = 400$m, $S_0 = 0.002$, $k = 40.1$ mm/hr[a], $a = 0.51$, $n = 0.15$, $d_{req} = 80$ mm, and $q_{in} = 2.5$ l/s/m. The recession time at the downstream end is well predicted with the Walker and Skogerboe (1987) procedures. However, Hart et al. (1980) provide a better estimate of upstream recession. In between, results are mixed.

5.3 Blocked-end Border Strips

Improvement in application efficiency can be obtained by blocking the downstream end of the border strip. This should only be done where the ponding depth, and associated infiltration time, will not cause crop damage. To limit crop damage, the end is sometimes partially blocked to limit the maximum ponded depth (e.g., by the elevation of overspill) or the maximum ponding time (e.g., by leaving a breach in the dike to allow it to eventually drain).

Where all the runoff is contained, the distribution of infiltrated water can be modified by assuming that the volume that ran off is ponded at the downstream end. Advance, recession and the distribution of infiltrated depths are computed as if for an open-ended border strip, then a ponded depth is simply added to the infiltrated depth at each location. The length of ponding can be found from

$$L_p = \sqrt{\frac{2V_{RO}}{S_0}} \tag{35}$$

where V_{RO} is the runoff volume. The ponded depth is zero at a distance L_p from the downstream end and is $S_0 L_p$ at the downstream end.

In the design procedures of the USDA (1974), the field length is adjusted to account for the ponding. In this design procedure, the cutoff time is adjusted, by trial and error, until the minimum depth matches the required depth. This will either occur at the upstream end or at a distance L_p from the downstream end. **This does not require any additional adjustments from simulation results. This same procedure is also used for furrows.**

6 Level-Basin and Level-Furrow Irrigation

6.1 Assumptions

With level-basin irrigation, rapid advance will produce a high uniformity. The design of basin irrigation systems is based on providing rapid advance, but without applying excessive amounts of water. In some cases, this requires cutoff prior to completion of advance. But with no field slope and only the water surface gradient to drive the water, cutoff with advance too far from the field end can give unpredictable results. Since the field is level, soil erosion is only a concern where water is turned into the field, i.e. locally. Minimum and maximum flow rates are not specified, but are dictated by the hydraulic conditions, i.e. design. With level basins, flow depth can become high and needs to be examined in design.

With the use of the zero inertia representative depth at both t_L and $t_{L/2}$, there is no longer any difference in advance calculations for level borders or furrows.

6.2 Flat-planted Level Basins

It can be assumed that recession occurs at the same time throughout the basin, the infiltrated volume can be determined by integrating depth (times width) over distance. A direct solution is not possible, but can be found through trial and error. An approximation can be obtained by representing the power advance function with a series expansion, as before (i.e. $x^h = 1 + h(x-1)$), Taking the first two terms in the expansion results in the following equation for the final infiltrated volume

$$V_z = LW \{ c + k\, \tau_{req}^a \frac{[(1 + hA_R)^{a+1} - 1]}{hA_R(a+1)} + b\,\tau_{req}(1 + \frac{hA_R}{1+h})\} \qquad (38)$$

where A_R is the advance ratio, advance time divided by required opportunity time. However, if the branch infiltration function is used, the solution is exact, provided that $_{req} > _B$. The resulting equation is

$$V_z = LW \{ d_{req} + \frac{bh\,t_A(L)}{(h+1)}\} \qquad (39)$$

The cutoff time is found by dividing this volume by the inflow rate, Q_{in}. For very small values of A_R, this equation is not appropriate, however in such cases the cutoff time can be based solely on required volume (i.e., assuming $PAE_{min} = 100\%$).

This procedure assumes that advance is complete prior to cutoff. For large level basins as used in the U.S., this is frequently not the case, particularly when flow resistance is high (e.g., alfalfa or grass). One of the biggest errors associated with this procedure is that the surface volume during advance is large. This is particularly true when cutoff precedes completion of advance. To avoid problems with this procedure, it should not be used when the advance is less than 90% complete.

WinSRFR uses an approximate procedure to adjust cutoff to provide a more representative estimate of the recession curve. The procedure determines the average depth infiltrated based on assuming horizontal recession with the required minimum depth at the downstream end. Simulation is then used to determine $_1$ for the following equation

$$t_{co} = t_{co-x} \phi_1 \frac{D_{req}}{D_{ave-x}} \qquad (40)$$

where t_{co-x} is the cutoff time for horizontal recession and D_{ave-x} is the average infiltrated depth for horizontal recession.

Figure 4 shows an example of advance and recession curves with simulation and from the procedures discussed above($_0 = 1$, $_1 = 0$). Specific include $L = 400$m, $S_0 = 0.000$, $k = 40.1$ mm/hr[a], $a = 0.51$, $n = 0.15$, $d_{req} = 80$ mm, and $q = 2.0$ l/s/m. Note that advance is not as well predicted as with the sloping methods. This may result from changes in the surface shape factor over time. Also, note how the recession curve is not flat, but has more opportunity time at the upstream end. This results from higher infiltration toward the downstream end where opportunity times are shorter.

6.3 Level Furrows and Furrowed Level Basins

Uses same procedures as sloping furrows.

7 Discussion

The set of equations provided above form the basis for computing actual designs. These equations do not lead the user through the design process. They only provide advance, recession and performance results based on preselected field length, width, inflow rate, infiltration, and roughness. However within WinSRFR, the equations are used to generate performance contour graphs. The calibration coefficients ($_0$, $_1$, $_2$, and $_3$) are determined at one location on the contour graph. The performance parameters are accurate at this calibration point, but drift off as one moves away from this point. WinSRFR also allows one to select a point on the graph for more detailed analysis. WinSRFR provides a comparison to simulation for this solution point. This allows one to see how well the contour graph represents the simulation solutions. If the contour graph is not sufficiently accurate in the area of interest, the user can select a new calibration point and recomputed the graphs.

8 Conclusions

In this paper, equations are presented that can be used to determine advance and recession curves for

- Sloping furrow irrigation, with and without cutback, and with or without runoff reuse
- Sloping border strips, either open or blocked
- Level basins, either flat planted or furrowed

The equations for advance use conservation of mass, but with the Manning equation, and a few coefficients derived from other sources. The advance equations only differ in how the friction slope is computed. For steep slopes, normal depth for the inflow is used, while for level fields, the water surface gradient and upstream depth are a function of the advance distance.

The equations for recession are different for each method. For very steep sloping furrows, one can assume that recession occurs everywhere at cutoff with little error. As the slope decreases, one can estimate recession by reducing the cutoff time by the volume of water on the surface at cutoff and assuming a linear recession curve from the time of cutoff at the upstream end to the advance time plus required opportunity time at the downstream end. For level basins and furrows, recession is computed with a volume balance based on assuming that recession occurs at the same time everywhere.

For border strips, recession is more difficult. Here, empirical equations are used for the difference in recession times between the upstream to downstream ends. Empirical relationships are also available for recession at the upstream end. The recession curve between these end points can be assumed a straight line, or can be constructed from an additional empirical relationship.

These equations should be useful for hand calculator and spreadsheet applications. Results from these equations are also used in WinSRFR to develop performance contours. WinSRFR uses simulation to adjust the performance contours to more accurately dis0play performance. The adjustment parameters used by WinSRFR are presented.

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Table 1. Categories of Surface Irrigation

Method	Control of lateral flow	Slope	Inflow control	End conditions
Sloping Furrow	Furrows	· Steep or · Low-gradient Either can have cross slope	To individual furrows	· Open, · Blocked, or · Group of furrows blocked
Border strip	· Flat planted or · Corrugations	· Steep or · Low-gradient Either can have cross slope	Distributed across upper end	· Open, · Blocked, or · Partially blocked
Level Basin/ Level Furrows	· Flat planted · Furrowed or bedded	Zero in all directions	Can be point inflow	Blocked If furrowed, all interconnected
	Furrows	Zero in direction of run, can have cross slope	To individual furrows	· Blocked, or · Group of furrows blocked
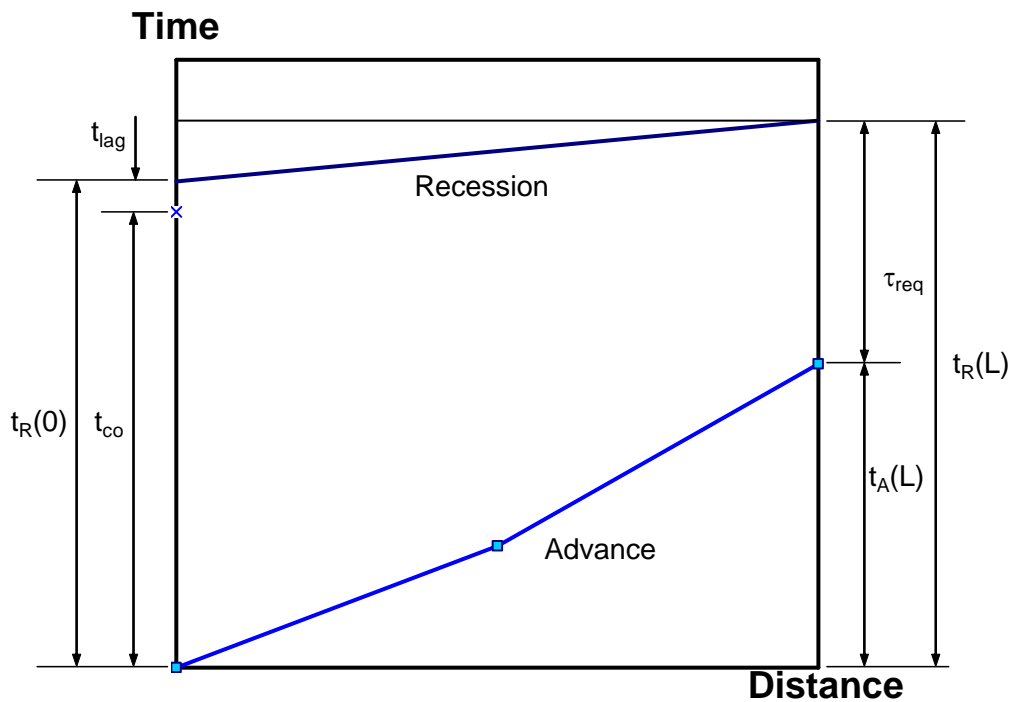
Figure 1. Advance and recession curves and definitions for design satisfying the target depth at the downstream end.
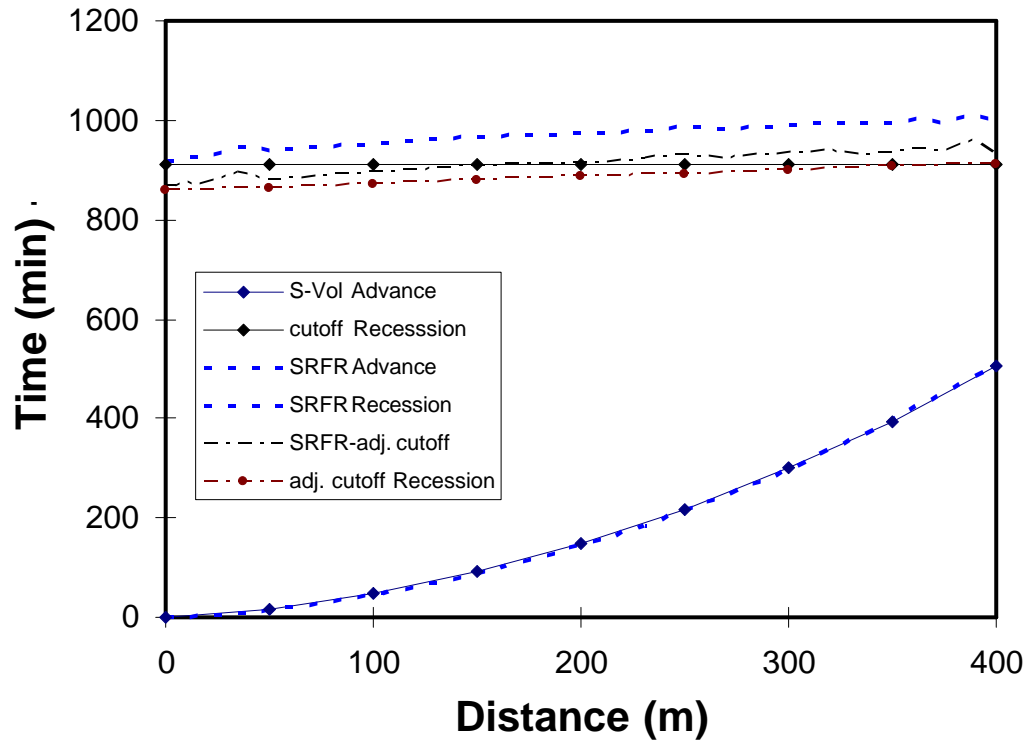
Figure 2. Comparison of furrow advance (from surface volume method and from SRFR simulation) and recession (from cutoff time, from adjusted cutoff based on furrow volume at time of cutoff, and from simulation with SRFR with original and adjusted cutoff times) curves.

Figure 3. Comparison of Border-strip advance (from assumed surface volume and from SRFR simulation) and recession (from original Walker and Skogerboe 1987, from adjusted procedure presented here, and from SRFR simulation).

Figure 4. Comparison of level basin advance (from assumed surface volume and from SRFR simulation) and recession (from uniform recession and from SRFR simulation) curves.

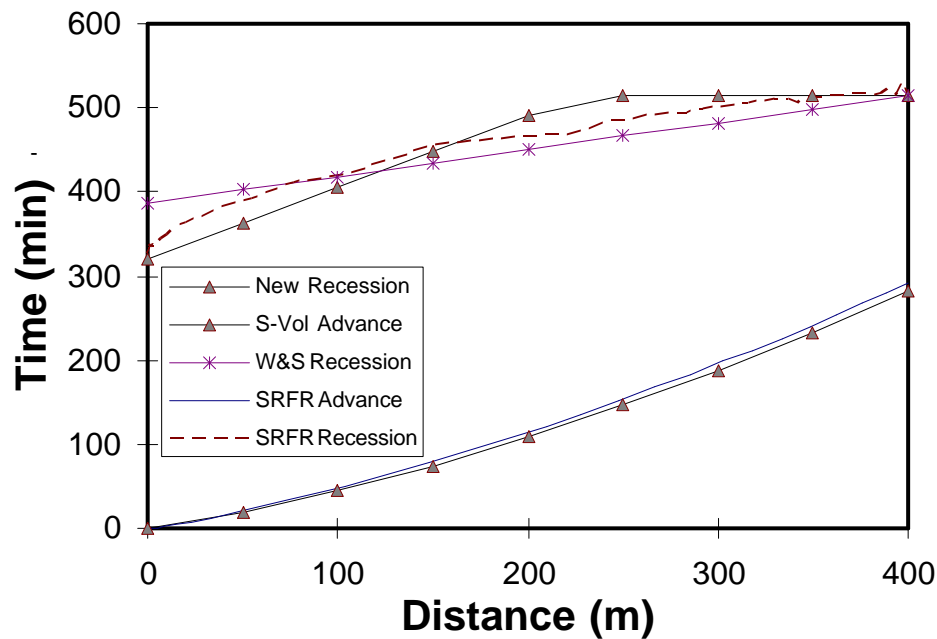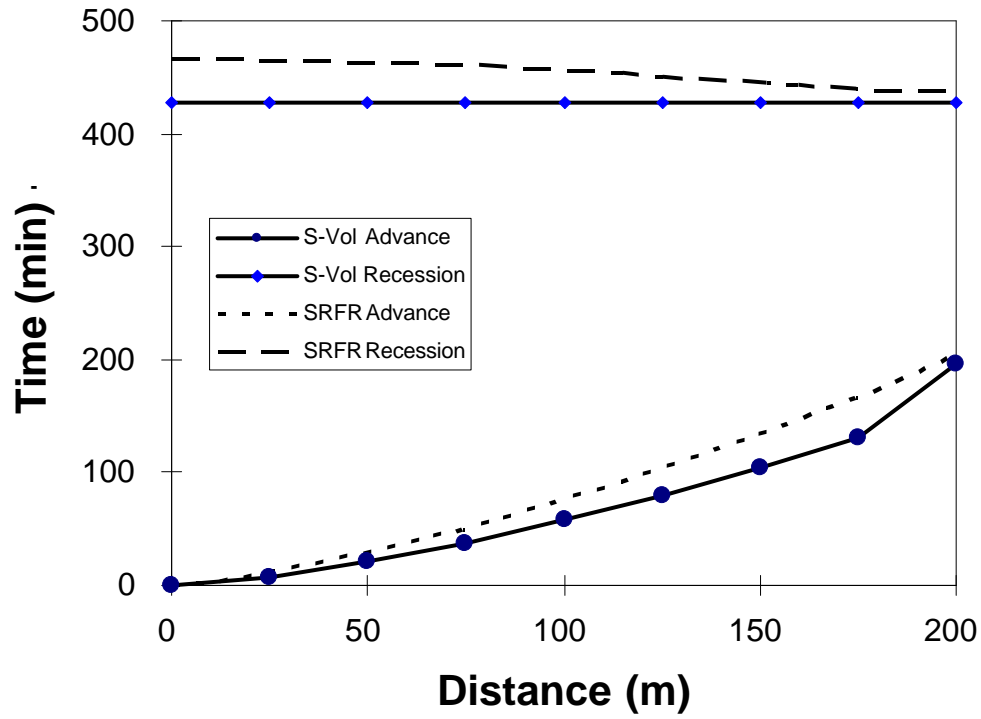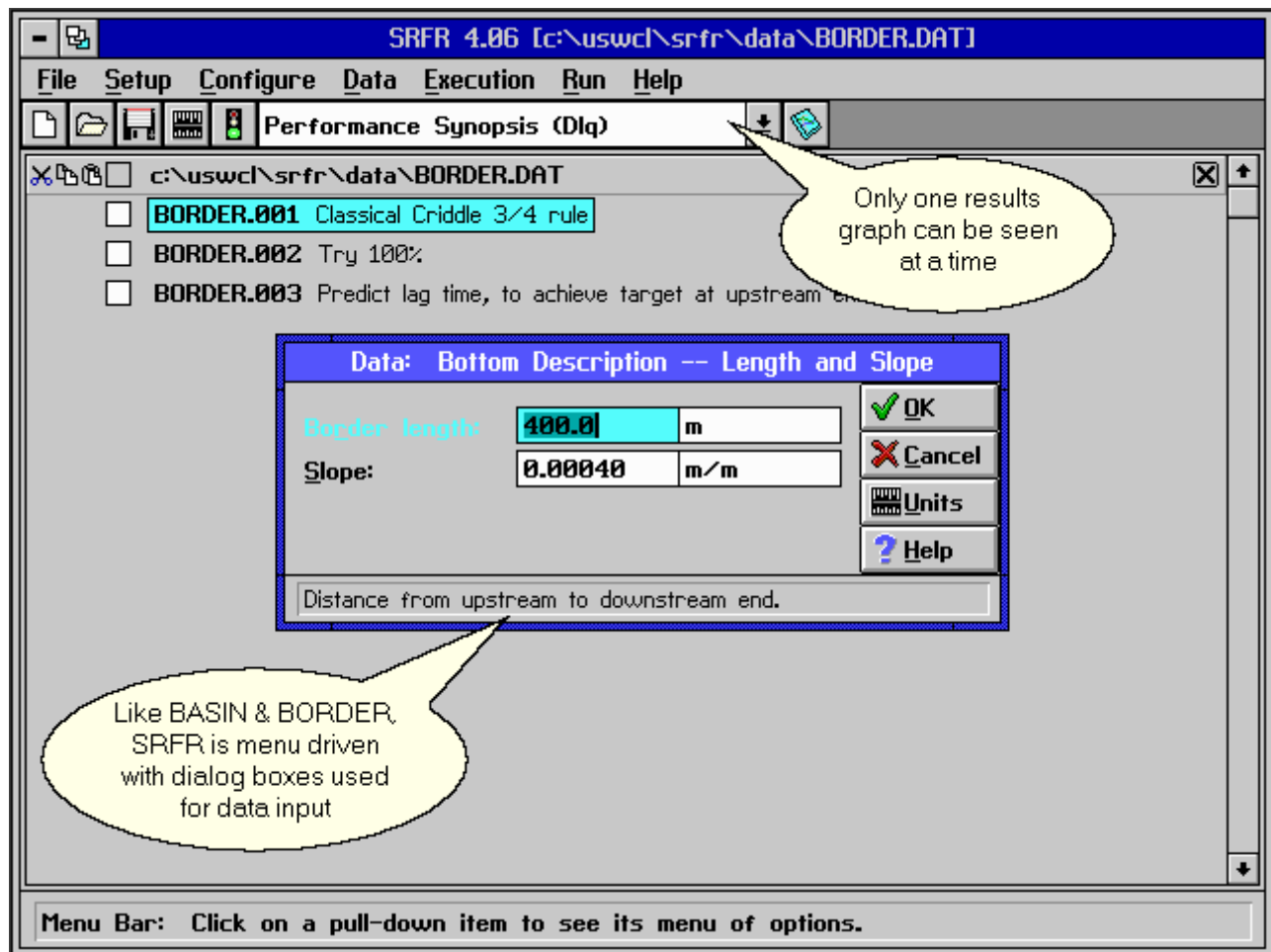## 5.3 SRFR

SRFR, a DOS program, is a one-dimensional mathematical model for simulating surface irrigation -- in borders, basins, and furrows. It is assumed that all flow characteristics vary only with distance from the inlet and time. No variation transverse to the main direction of flow is considered. Thus, any cross slope in borders and basins is assumed negligible; also, the inflow therein is assumed distributed uniformly across the width. Only single furrows are considered; neighboring furrows are assumed to have identical flows --any variation in properties from furrow to furrow within a field must be modeled separately. On the other hand, field properties like the infiltration characteristics and roughness, bottom slopes, and furrow cross sections for example, can have a prescribed variation with distance along the bed, and even with inundation time.

The results of a simulation, like those of an actual run in the field, depend on the hydraulic properties of the soil and crop (if the vegetation is immersed in the flow), the physical design of the system (length, slopes, etc.), and the irrigation management: flow rates, duration, etc., as well as the target depth of infiltration for the irrigation. When all of these quantities are prescribed by the user -- through the interactive data-entry windows -- the simulation can be performed. The results – the advance and recession curves, the runoff, and the distribution of infiltration depths along the length of the run when recession is complete -- can be presented both graphically, and numerically through a series of performance indicators, such as application efficiency, distribution uniformity, adequacy of irrigation, water cost per application, etc. Moreover, the graphical results of several simulations

under different conditions can be superimposed in different colors for convenient comparison. During the course of each simulation, an animated graphic of the soil and water surfaces and the growing infiltration profile in the soil are displayed.

Simulations consist of numerical solutions of equations which represent, mathematically, universal physical principles like conservation of mass and momentum. These general equations are complemented by user-given conditions of the irrigation to make a specific solution possible.

The latest release, SRFR 4.06, occurred on November 18, 1999.

The Run menu is used to execute the selected function and the results are displayed as graphs, some with additional parameter lists. An animation showing the surface water flow and infiltration is displayed while the simulation is running.
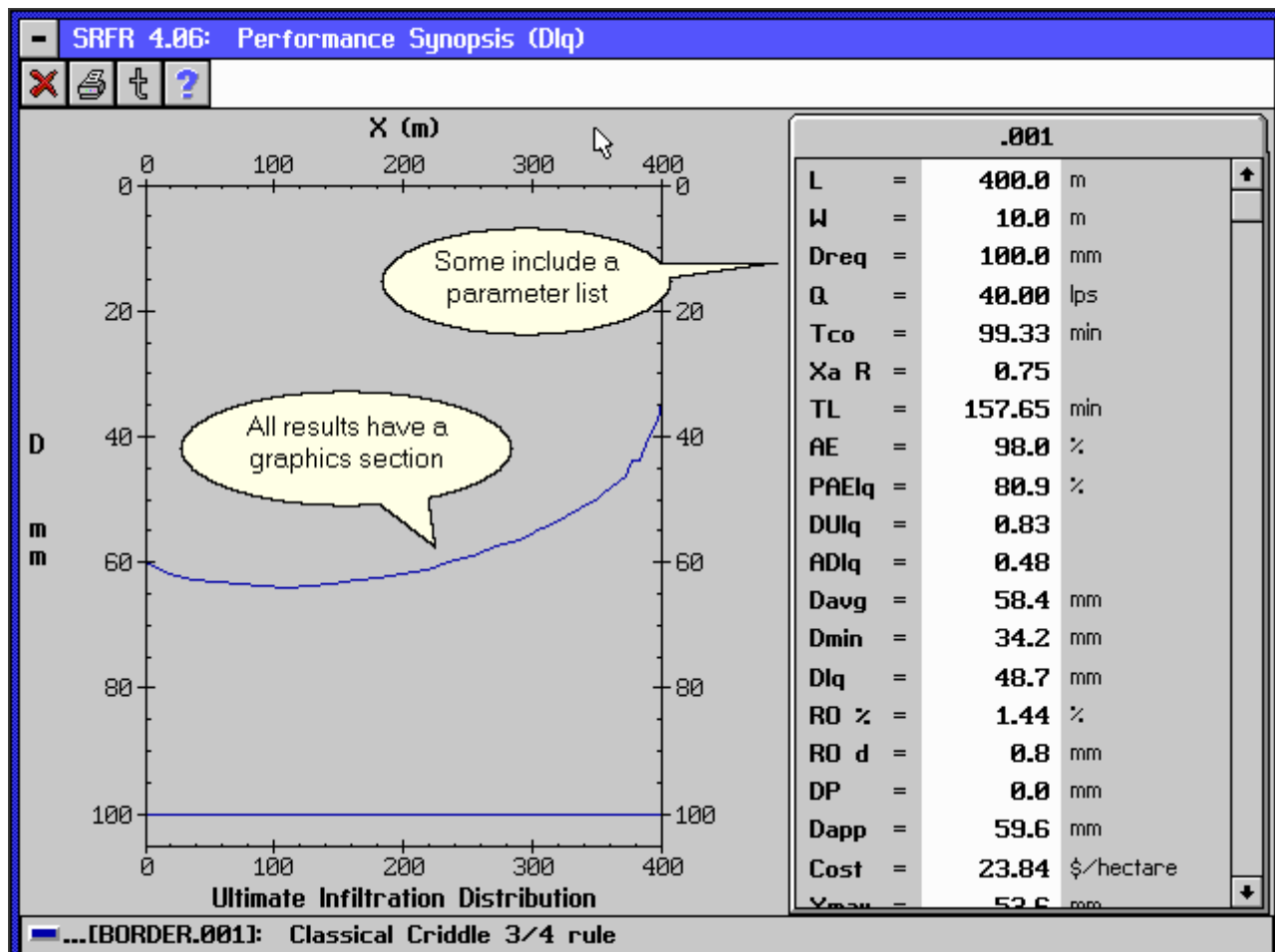
SRFR produces graphs for several performance parameters one of which is the Performance Synopsis (Dlq) shown above.

The following text was edited from SRFR's manual and help system to make it compatible with WinSRFR's incorporation of SRFR's functionality.

SRFR -- Overview

SRFR is a one-dimensional mathematical model for simulating surface irrigation -- in borders, basins, and furrows. It is assumed that all flow characteristics vary only with distance from the inlet and time. No variation transverse to the main direction of flow is considered. Thus, any cross slope in borders and basins is assumed negligible; also, the inflow therein is assumed distributed uniformly across the width. Only single furrows are considered; neighboring furrows are assumed to have identical flows --any variation in properties from furrow to furrow within a field must be modeled separately. On the other hand, field properties like the infiltration characteristics and roughness, bottom slopes, and furrow cross sections for example, can have a prescribed variation with distance along the bed, and even with inundation time.

The results of a simulation, like those of an actual run in the field, depend on the hydraulic properties of the soil and crop (if the vegetation is immersed in the flow), the physical design of the system (length, slopes, etc.), and the irrigation management: flow rates, duration, etc., as well as the target depth of infiltration for the irrigation. When all of these quantities are prescribed by the user -- through the interactive data-entry windows -- the simulation can be performed. The results -- the advance and recession curves, the runoff, and the distribution of infiltration depths along the length of the run when recession is complete -- can be presented both graphically, and numerically through a series of performance indicators, such as application efficiency, distribution uniformity, adequacy of irrigation, water cost per application, etc.
Moreover, the graphical results of several simulations under different conditions can be superimposed in different colors for convenient comparison. During the course of each simulation, an animated graphic of the soil and water surfaces, and the growing infiltration profile in the soil are displayed.

The simulations consist of numerical solutions of equations which represent, mathematically, universal physical principles like conservation of mass and momentum. These general equations are complemented by user-given conditions of the irrigation to make a specific solution possible.

Infiltration

SRFR allows five different ways to enter the infiltration characteristics of the subject field. In every case, however, the ultimate description is cumulative infiltration depth, d (volume per unit area), based on a power law in opportunity time t (Kostiakov equation). This can be augmented by a constant, c, representing the essentially instantaneous intake upon initial contact of water with soil (as in cracking soils). Furthermore, a final, long-time infiltration rate, b, is recognized. Thus, a modified Kostiakov equation (or, alternately, a Branch Function, detailed below) is used to describe infiltration in SRFR:

$$d = k * t^a + b * t + c$$

in which k, a, b, and c are constants. The coefficient k represents the depth infiltrated in a unit of time (e.g., hour or minute); a, the exponent, controls the reduction in infiltration rate with time. The smaller is a, the sharper the reduction in infiltration rate, and the more pronounced is the "dog leg" in a plot of cumulative infiltration vs. time. The theoretical value for uniform fine-grain sand in the early stages of infiltration is 0.5, increasing somewhat with time as the soil near the
surface is saturated. Soils with a high clay content tend to exhibit smaller values.

On logarithmic paper, the plot of (Kostiakov) cumulative infiltration vs. time is always a straight line, with a representing the slope of the line, and k the intercept at 1 unit of time (hour or minute: user selectable -- see Help: System of Units). A non-zero value of b causes the line to curve upwards, with increasing t, gradually approaching a slope of unity. A non-zero value of c causes the line slope gradually to decrease, at the smaller values of t, as cumulative infiltration approaches the constant value.

A further modification of the Kostiakov formula is provided by the Branch Function, suitable for many soils, which recognizes the final infiltration rate as taking over at the time at which the rate given by the original Kostiakov formula equals that final rate. Thus, infiltration depth is assumed to increase, initially, according to the relation:

d = k * t^a + c

and when the time rate, d/dt (d), equals the specified final rate, b, infiltration continues indefinitely at the constant rate, b.

A particular approach to establishing the infiltration-formula constants is chosen by selecting one of the following options.

1. Time Rated Intake Families
2. Modified Kostiakov formula
3. Branch Function
4. Known Characteristic Infiltration Time
5. SCS intake families

For a given soil, the numerical values of the infiltration-formula constants are heavily dependent on the assumption made for the effect of wetted perimeter on infiltration. Approximately, for a given soil, the Kostiakov coefficients, except for the exponent a, are inversely proportional to the effective wetted perimeter. The default wetted perimeter for infiltration is the furrow spacing, except in the case that the SCS intake families are selected -- then it is the value given by the SCS empirical wetted perimeter formula.

Soil infiltration characteristics are particularly important in their effect on irrigation performance, yet at the same time are often poorly known. In such case, if the user can at least estimate the time the soil requires to infiltrate a depth of 100 mm (4 inches), the empirical relationship incorporated into the Time-Rated Intake Families (for non-cracking soils) can provide an estimate of the other characteristics.

In the 1970s, the Soil Conservation Service (now NRCS) devised a system of characterizing soil infiltration by membership in a group of families (USDA, 1974). The name of the family, a decimal number, was related to the final (basic) infiltration rate (in inches per hour) exhibited by the soil after a long period of infiltration. Cumulative infiltration for each family is described by an expression of the form,

d = k * t^a + c

a plot of which on logarithmic paper exhibits a slight curve. Each family is defined by particular values of K and A; C is the same for all families. In other words, the SCS families are characterized by a specific relation between the name, K, and A. All of the A values are somewhat higher than 0.5, and all families, if graphed, form a regular progression of curves without intersections. While many soils fail to fit any of the families (graphs of their cumulative infiltration vs. opportunity time intersect many SCS-families), some are, indeed, successfully incorporated within the SCS group. The opportunity to describe soil infiltration is provided for those users whose experience justifies describing their subject soils in this way.

When entering field infiltration data for furrow flow, the user should take care to note the selected assumption for wetted perimeter for infiltration, because this selection materially affects the appropriate value of accumulated depth. The wetted perimeter for infiltration is multiplied by the time rate of increase of cumulative depth to yield the time rate of increase of accumulated volume per unit length of furrow. For a given physical furrow infiltration, a volume per unit length, the wetted perimeter for infiltration and the depth of infiltration are inversely proportional.

The default wetted perimeter for infiltration is the furrow spacing (unless an SCS Intake family has been selected

to characterize soil infiltration).

Infiltration -- Time Rated Intake Families

The user enters the limiting depth of infiltration, if any. This might be caused by an underlying layer of clay or hardpan. If infiltration is not limited, 0.0 is entered.

With time-rated intake families, the single entry, the time to infiltrate 100 mm (4 inches), defines the infiltration characteristics of the soil. The result is a Kostiakov formulation in the form $k\,t\,\hat{}\,a$, with the exponent a empirically tied to the characteristic time entered, and hence not independently selectable.

Infiltration -- Modified Kostiakov Formula: $k * t\hat{}a + b * t + c$

The four parameters of the formula are entered. Inasmuch as the units of the Kostiakov coefficient k are depth per unit time-raised-to-the-power-a, the numerical value of k depends strongly on the time units. Thus, the user first selects the unit time (hour, minute) at which k constitutes the intercept in the graph of the Kostiakov equation, and then enters k.

The user then enters the limiting depth of infiltration, if any. This might be caused by an underlying layer of clay or hardpan. If infiltration is not limited, 0.0 is entered.

Infiltration -- SCS Intake Families

The user enters the limiting depth of infiltration, if any. This might be caused by an underlying layer of clay or hardpan. If infiltration is not limited, 0.0 is entered.

The user enters the family name for the SCS intake family thought to best represent the infiltration characteristics of the soil. Selection of this infiltration-specification option implies also (by default) a corresponding wetted perimeter for infiltration given by the SCS empirical formula.

The SCS intake formula has the form $z = k\,t\,\hat{}\,a + c$, in which k and a depend on the family number in accord with a published table, and c is a small constant (0.275 inches, or 7 mm), intended to make a better fit to field data. At low flows on very large slopes, the depth of flow can be of the same order of magnitude as this constant, and even smaller. This implies an enormous infiltration to the advancing flow, leading to a spasmodic simulated advance. This artificial problem is avoided if the pertinent SCS family is approximated by a best fit Kostiakov formulation, $k * t\,\hat{}\,a$. This option is selectable (and is the default) upon selection of the SCS families for characterizing infiltration.

The default wetted perimeter for infiltration characterized by an SCS intake family is the SCS empirical wetted perimeter, generally somewhat larger than the actual wetted perimeter of the furrow (for other characterizations of infiltration, the default wetted perimeter for infiltration is the furrow spacing).

Wetted Perimeter

These options are available only at the Advanced Level.

Five assumptions on the effect of wetted perimeter on furrow infiltration are available in SRFR. It is essential to recognize that the coefficient values in the infiltration formulas are dependent, sometimes heavily so, on the assumption made here. Approximately, for a given soil, the Kostiakov coefficients, except for the exponent a, are inversely proportional to the effective wetted perimeter.

Local wetted perimeter means that the increase in volume infiltrated per unit length in a time step is given by the

increase in depth multiplied by the current wetted perimeter.

The second choice multiplies the depth increase by the wetted perimeter at the upstream end.

Alternately, the wetted perimeter calculated from normal depth at the inflow end of the furrow is used.

A very simple assumption, particularly appropriate with cracking soils, is for the nominal wetted perimeter for infiltration to be the furrow spacing.

The SCS intake families were developed for furrow irrigation with an empirical wetted perimeter in mind. This wetted-perimeter function is the default option for the selection of the SCS families in the previous window, but the Advanced user can change this to any of the above to study the effect of this assumption.

Resistance to Flow -- Manning n

Both soil-surface drag and the drag of inundated vegetation on the flowing irrigation stream are assumed to be characterized by a single value of the coefficient n in the Manning formula, independent of both flow rate and depth. For a given flow rate and bottom slope, a large value of n leads to a large flow depth, a small value to small depths.

The standard user can select either to supply a numerical value for the Manning n, or accept the values suggested by the SCS for a number of soil and crop conditions. Recent measurements suggest that the SCS recommended values may be somewhat low.

Roughness -- Manning n

Enter a value for the Manning n.

Roughness -- SCS Suggested Manning n

Recent measurements suggest that the SCS recommended values may be somewhat low.

Enter your selection of SCS recommended value.

These options are available only at the Advanced level:

If appropriate field data are available, the Manning n value can itself be allowed to vary as a power law of water depth -- to reflect the formula's inherent unsuitability for shallow flows with large roughness elements. Thus, if no variation with depth is assumed, the coefficient Cn is the constant value of the Manning n; otherwise, Cn is the coefficient and An the exponent in a power-law relationship.

An alternative resistance formula, more physically based than the purely empirical Manning formula, is the logarithmic Sayre-Albertson relationship, similar in its origins and form to the Colebrook-White expressions for pipe flow. Here the absolute roughness of the soil surface is given by the variable, chi, measured in units of length. Despite its theoretical advantages, typical field values of chi are not generally known.

Submerged vegetation plays a role in resistance to water flow quite different from that of the soil surface. While the latter exerts shear only at the flow boundaries, vegetation exerts a form drag over the entire depth of submergence, depending heavily on the density of growth -- measured as frontal cross-sectional area per unit plan area of the flow channel (typically a border strip, or basin) per unit depth. The units of vegetative density are L^{-1}. Evaluation of vegetative drag, which can be substantially greater than the drag of the soil surface, is still in an

experimental stage. For example, in a laboratory setting, with artificial vegetation in the form of vertical wires of diameter D uniformly spaced on a grid with N wires per unit floor area of a flume, the vegetative density is ND. In the field, it is still common practice to lump the two components of drag, surface and vegetative, together and express the result through a constant value of the Manning n, ignoring the form-drag characteristics of submerged vegetation altogether.

Roughness -- Manning N Advanced, Vegetative Drag

The fundamental unsuitability of the Manning formula for shallow flow in channels of high roughness has suggested allowing the Manning n to vary with depth, specifically as a power law in depth. Cn represents the coefficient in this power law, i.e., Manning n at unit depth, while An is the exponent in the power law. If there is no variation in Manning n with depth, Cn is the constant n value, and An=0.

Also enter the vegetative density, assumed independent of depth

Roughness -- Sayre-Albertson Chi, Vegetative Drag

The Sayre-Albertson chi, possessing units of length, is a measure of absolute roughness of the flow channel. It is essentially an indicator of the height of the roughness elements, but is influenced by the micro-geometry: element shape, size distribution, spacing density, etc. The Sayre and Albertson logarithmic formula for hydraulic drag, in general, follows drag variations with depth more closely than the Manning formula, but its structure does not permit the hydraulic radius of flow to be less
than chi. In fact, at a hydraulic radius equal to chi, the calculated drag is infinite.

Any distance or time variation in the Sayre and Albertson chi value is entered in a table, constructed by the user in the data window by inserting lines as necessary. The + button in the table brings up time levels at which parameters are to be defined.

Vegetative density is expressed in area of vegetation facing the flow, per unit plan area, per unit depth. It is assumed independent of depth. Drag per unit length of flow is calculated from the estimated form drag of the vegetation.

Inflow Management

Allowable inflow-time patterns are the standard, consisting of a single pulse of given rate and duration, but allowing for cutback and a table of flow rate vs. time.

Inflow Management -- Standard Hydrograph

The time component of the inflow hydrograph can be specified either in terms of so many hours or minutes from the start of the irrigation, or in terms of the location of the stream front, when a change in flow rate (either a cutback or cutoff) is to be initiated.

Cutoff based on distance can depend in various ways on the stream behavior. This matter can be explored in the screen activated by pressing More, available only to the advanced user.

These options are available only at the Advanced level:

Downstream control of inflow depends upon the advance of the irrigation stream down the field. Inflow can be cut off when the stream reaches a given point down the length of run, or when a given infiltration depth has accumulated there, or when the point has experienced a given infiltration-opportunity time.

Upstream control, available only in sloping border strips, is designed to cut off the inflow at such time that the target depth is infiltrated at the upstream end just as recession begins there. The prediction of lag time necessary to specify such cutoff is performed by internal software interpolating within a dimensionless database of previously run simulations.

System Geometry

The choices reflect the allowable variations in system geometry with distance down the length of run.

The selection of furrow cross-section description or border or basin irrigation is made here. The (symmetrical) furrow cross section can be assumed approximated either by a trapezoid or by a power law in which the water-stream top width is assumed to vary in proportion to water depth raised to some exponent.

A Border Strip can have either an open end or a blocked end. Open End means free fall into a drainage ditch; Blocked End means no runoff whatsoever. Flat-planted Basins are not furrowed, are blocked at the downstream end, and can be set to any slope. They are equivalent to closed-end border strips.

Drainback into the supply ditch is enabled by checking this box in the Upstream boundary condition. Backflow begins when the water level in the supply ditch drops below the upstream surface elevation of the irrigation stream. Drainback, with its negative inflow after cutoff, allows higher efficiencies and greater control in basin irrigation, particularly with small target depths of infiltration, than simply cutoff to zero inflow. This option is allowed only with the standard or tabulated inflow hydrographs, and with the Zero-Inertia simulation mode.

Specification of the longitudinal bottom configuration can be made either in terms of bottom slopes or a table of distance vs. elevation.

Simulation Control

The advanced user can select a basis for simulation.

The Saint Venant equations contain all the acceleration terms in an unsteady open channel flow; these are typically very small in surface-irrigation flows.

The Zero-Inertia model deletes the acceleration terms to provide a more robust simulation. This is tantamount to assuming that the forces stemming from depth variations with distance, bottom slope, and hydraulic drag are in equilibrium. Comparisons with solutions to the Saint Venant equations show that this assumption is adequate in surface irrigation.

As the slope of the flow channel increases, the zero-inertia formulation becomes increasingly difficult to apply, requiring subdivision of the advancing-stream length into many small cells, especially at the downstream end, where depth increases very rapidly with distance back from the front. These computational difficulties are avoided by utilizing the Kinematic-Wave mode of solution.

For steep slopes, the contribution of the depth gradient to the force balance is very small and can be neglected, leaving equilibrium between the force of gravity downslope and the hydraulic drag upslope. This is the basic premise of the normal-depth kinematic wave.

The default transition between zero-inertia and kinematic-wave formulations lies at a bottom slope of 0.001.

Simulation Control -- Cell Density

Cell density influences the number of cells into which the stream is divided for the numerical simulation. Furthermore, the smaller the cell size, the smaller is the initial time step. The time step typically grows with time, depending on the behavior of the simulation, while the cell sizes are fixed with time.

A coarse grid selects 1/5 of the length of run for the initial cell size; medium, 1/10; fine (a typical default), 1/20; and extra fine, 1/40. Smaller cells are accommodated by entry of numbers greater than 40, following selection of Numerical Entry.

Simulation Control -- Numeric

This experimental group of parameters are available only to users at the program-developer level. They should not be changed without consultation with the Arid-Land Agricultural Research Center, Maricopa, Arizona, as modifications can result in unexpected simulation behavior.

The most physically based parameter is YTREC, a water depth below which recession is assumed to occur. While depths within the computational boundaries can be less than YTREC, recession time for a point is determined by the time its depth crosses YTREC. YTREC is defaulted to 1/2 millimeter (see sample data file, DUNKLIN, for effect of various YTREC when infiltration is negligible -- stopped by an impenetrable layer beneath the soil surface).

NYUBC is the number of time steps over which the drop in inflow water depth to zero is assumed to occur in drainback operation of a basin upon cutoff (S 1360).

NIWAIT is the number of times that the Newton-Raphson correction vector is allowed to be shortened to forestall premature recession.

IT40 is a flag pertinent to selection of cutoff when a given depth has infiltrated at a given point along the length of run. If IT40 is set to 1, cutoff is initiated, instead, when the low-quarter average of infiltrated depth equals the given value.

RDFCT, defaulted in shell to 0.0, and in engine (I1.FOR) to 1.0; used in SA 6020+: if I=IPTQBK-1, RCMAX=RCMAX*RDFCT, RMMAX=RMMAX*RDFCT.

NDXKG is the minimum number of cells between KG (S 1350). Defaulted in shell to 0, in engine, to 1.

VDB1 is used in subroutine VOLUME_BASED_DT (666): VQ_KRB(1)=VDB1*DELTA_VZ_KRB. Any shell value less than 1.0 is changed to 1.0 in the engine.

DTLRAT is the fraction of field length constituting the minimum allowable advance increment (S 100-). Shell default is 0.5; this (or any value .LE. 0.0) leads to engine value of 0.005

QCOAVG, Auto RDT (group3autoRDTChange in DATA.FI), IDT (group3IDTChangeMax in DATA.FI) not used (SRFR 4.06)

Simulation Control -- Solution

The advanced user can override the default values for certain parameters of the numerical solution.

The simulation runs in dimensionless mode: physical variables are divided by reference variables with the same dimensions to yield dimensionless counterparts. Two systems are available in SRFR. One, based on normal depth at the given inflow in the given flow channel, is only possible in sloping channels and is the default for sloping channels. The other, based on a reference time (equal to cutoff time, if that is known), is the necessary default for horizontal channels, or those with adverse

slope.

RDTSTG is the rate at which the solution time step is intended to increase, if and when the irrigation stream forms an essentially stagnant pool (SA 4440) (default: 1.2).

R0 (timeStepCtrlR0) is the dimensionless first guess for depth at the end of the first time step of advance. Any value set here < 0.05, will revert back to 0.1 in the engine.

R1 (iterationCtrlR1) is not in currently in use (SRFR 4.06).

FILFT is the weighting coefficient for left-side cell values in determining an average. Right-side values are multiplied by (1-FILFT). In zero-inertia and St. Venent modes, FILFT defaults to 0.5, while in KW mode, the default is 0.0.

STOPI is the maximum number of time steps to be run in the simulation. An upper limit has not been established; the default is 1451.

TSTOP is, similarly, an upper time limit on the simulated irrigation. The default is one week.

RCMXR and RMMXR control the tolerance to which the conservation-of-mass and conservation-of-momentum equations must be satisfied to complete a time step. These are both decimal fractions of the sum of the absolute values of the terms in the equations.

If the number of iterations required to satisfy the tolerances exceeds JHI (default: 7), the subsequent time-step sizes will be decreased.

If they fall below JLO (default: 6), the time step will be increased.

JMAX is the number of iterations allowed for convergence before corrective action is taken (default: 20).

JCOUNTMAX is the total number of iterations allowed in one time step (default: 60).

Simulation Control - Diagnostics

For troubleshooting, the SRFR simulation engine writes diagnostic information of various types to the file SRFR. DGN housed in the subdirectory, DIAGNSTC, a child of the one containing the SRFR program files. To strike a balance between utility and ponderousness, the user should select judiciously the type of information written. The file can easily grow in size to tens of megabytes.

Additional "diagnostic" flags are made available for experimental transmission of Soil Erosion/Transport information to SRFR.

Simulation Control - Graphics

This window controls the appearance of the animated surface-water and infiltrated-depth profiles generated in the course of the simulation. It also enables recording hydrographs and stream profiles during the simulation.

The first choice, Profile Forms, determines whether elevations or depths are plotted. Selection is made by scrolling with the arrow and clicking on the desired option. Elevation plotting identifies a sloping soil surface, at the bottom of a furrow or in a basin or border strip. Surface-water flow depths are shown above that line, to the same scale as the soil-surface elevations, and depths of infiltration are shown below it.

In steep slopes, the change in bottom elevation over the length of run dwarfs the surface-water depths, and the

profile of the surface stream becomes barely visible. To discern its configuration (and the behavior of the simulation), it is necessary to plot depths, instead of elevations. The sloping soil surface, then, is not shown sloping, and the surface-water flow depths occupy a significant portion of the screen. The disadvantage to this kind of plot is that behind any obstruction in the flow channel (say a blocked end), flow depth rises, and the plot appears to show an upward sloping water surface. When it is recalled that the water surface shown represents depth, and not water-surface elevation, this problem vanishes.

The remaining entries relate to the scales to which the animation is shown. By default, scales are chosen which will in most cases adequately accommodate the entire simulation. Manipulation of the 5 ratios, RLLEFT, RLRGHT, RYBOT, RYTOP, and RFSZ enables zooming in to magnify some portion of the area of animation.

The default horizontal full scale is the length of run.

RLLEFT (default: 0.0) specifies the fractional length of run comprising the left boundary of the display, and RLRGHT (default: 1.0) specifies the fraction of length of run comprising the right-hand boundary of the display.

For example, to limit the display to the region between 80% of field length and 90% of field length, set RLLEFT=0.8 and RLRGHT=0.9.

Similarly, the default vertical full scale allows plotting points between the lowest bottom elevation and the field surface (or border berms).

RYBOT (default: 0.0) is the fraction of this full scale below which elevations are not shown, while RYTOP (default: 1.0) is the fraction of this full scale to which elevations are shown.

Depths of infiltration are always shown from 0.0 to some full scale.

RFSZ (default: 1.0) is the fraction by which the default full scale is multiplied.

RFSX, RFSY, RFSH, play similar roles and will not survive if user experiences demonstrates no need.

The Profile Table provides a list of irrigation times at which a record of the surface-water profile is desired (recall that all of the graphed information is stored in a text file which can be viewed from within SRFR or in any text editor; the file bears the same name as the data file, and an extension identical to the simulation number).

Hydrographs are prepared, by default, at the inflow and outflow sections. Discharge and depth can be recorded also at intermediate locations, to be entered in the Hydrograph Table in this window.

Results

Performance Parameters are headed by a restatement of salient input conditions: length of run, border-strip width or furrow spacing, target depth of infiltration for the irrigation, inflow rate, and final cutoff time. The performance of the irrigation is then displayed in the following terms:

- **XCO** - advance at cutoff (if this is less than field end).

- **TL** - time for stream to advance to field end.

- **AE** - application efficiency, defined as volume infiltrated within the target depth, in ratio to the total volume of inflow, expressed as a percent.

- **PAEmn** - potential application efficiency of the min, is the application efficiency calculated on the basis of a new target depth, exactly equal to the minimum of the simulated distribution. Note that this is different from the standard definition of PAEmn, which calls for a cutoff time of just such magnitude that the resulting minimum depth just equals an independently given target depth. A simulation based on an arbitrary cutoff time cannot yield this value.

- **PAElq** - potential application efficiency of the low quarter, is the application efficiency calculated on the basis of a new target depth, exactly equal to the average of the simulated low quarter of the distribution. Note that this is different from the standard definition of PAElq, which calls for a cutoff time of just such magnitude that the resulting low quarter depth just equals an independently given target depth. A simulation based on an arbitrary cutoff time cannot yield this value.

- **DUmin**, the distribution uniformity of the minimum, is the ratio of the minimum depth of infiltration in the post-irrigation distribution to the average infiltration depth.

- **DUlq** - distribution uniformity of the low quarter, is the ratio of the average of the low quarter of infiltration depths to the average infiltration depth.

- **ADmin**, adequacy of the minimum, is the ratio of the minimum depth to the target depth of infiltration.

- **ADlq** - adequacy of the low quarter, is the ratio of the low-quarter average depth to the target depth of infiltration.

- **Dinf** - average depth of infiltration in the length of run after the irrigation is completed.

- **Dmin** - minimum depth in the post-irrigation infiltration distribution.

- **Dlq** - average of the low quarter of post-irrigation infiltrated depths in the length of run.

- **RO %** - percentage of the inflow that runs off the end of the field as tailwater.

- **RO d** - volume of runoff, expressed as a depth over the field.

- **DP** deep percolation, represents the volume of infiltration, locally in excess of the target depth, expressed as a depth over the field.

- **Dapp** applied depth, is the volume of inflow expressed as a field depth.

- **Cost** - cost of irrigation water per unit area of field.

- **Ymax** - maximum depth of water in the border strip, basin, or furrow and indicates the degree of freeboard available. If an overflow condition has occurred during the simulation, the word OVERFLOW! appears. (Overflow is accounted for in furrow irrigation by means of the physical assumption that neighboring furrows on either side have identical flows; overflow is not accounted for in border or basin irrigation.)

The Performance Synopsis graph displays the longitudinal post-irrigation distribution of infiltrated water, as well as a series of numerical performance indicators: efficiency, uniformity, etc. The user can select performance based on the minimum depth in the distribution, or on the average low-quarter depth. And the distribution curve can be selected either as reflecting the actual, physical location of each infiltrated depth, or else ordered by magnitude, i. e., simply ranging from maximum to
minimum, as a function of the percent of field area with that amount or more infiltrated.

The Hydraulic Summary is a combination graph, showing for each selected simulation: the inflow hydrograph, the

advance and recession curves, the runoff hydrograph, and the longitudinal post- irrigation distribution of infiltrated water.

The Advance and Recession curves show these trajectories on a common set of axes.

If recession takes place well after the end of the advance phase, the time scale needed for plotting the two together makes the advance appear instantaneous. To view the behavior of advance with time, select the Advance Trajectory graph.

The longitudinal post-irrigation distribution of infiltrated depths can be viewed either as a function of distance down the field, or ordered in magnitude (see Performance Synopsis, above).

The infiltrated depths shown are field depths -- i.e., volumes per unit plan area of field, and so, for furrows, incorporate both the assumption made for the influence of wetted perimeter on infiltration and the furrow spacing.

The inflow, outflow (runoff), and any selected intermediate flow hydrographs are superimposed on a single time scale in this option.

Alternately, the inflow, outflow, and any selected intermediate depth hydrographs can be viewed superimposed on a single time scale in this option.

Water-surface-elevation profiles developed at selected times during the irrigation are viewed with this option. Alternately, depth profiles can be viewed.

Simulation Animation

The screen is broken into two regions. The upper portion shows the irrigation stream, with its surface above the bottom of the flow channel a distance equal to the actual depth. The lower portion of the split screen displays the infiltration profile, drawn at a distance equal to volume infiltrated per unit field area. Thus the significance of the depth scales above and below the channel bottom is not exactly the same.

The water surface in isolated depressions sometimes appears humped, rather than level. This stems from the simplifying assumptions made to speed up the calculations of infiltration from such ponds. The effect on the infiltration distribution and recession times is negligible.

Shown on the animation frames (and influencing the vertical scale) are the top of the furrow (or top of border or basin berms). During periods of overflow (accounted for in furrow simulations with the physical assumption that neighboring furrows on either side have identical flows; not accounted for in border or basin simulations), a message appears on the screen, near the point of overflow.

The top of the furrow (field soil surface) or berms is assumed fixed with time, as the flow-channel bottom changes with assumed erosion or deposition.

Also shown is the target depth of infiltration. The default vertical scale is influenced by this amount, and by the total expected depth of infiltration.

6   Terminology

Water Flow

Q   - Inflow Rate

R   - Cutoff Ratio - Ratio of advance at cutoff to field length.

Tco   - Cutoff Time

TL   - Advance time to end of the field.

Infiltration

Kostiakov Formula: $Zn = k * Tn^a$

Zn   - Infiltration depth at time Tn.

k   - Coefficient constant. Represents the relative ease at which water infiltrates into the soil. The larger **k**, the easier water infiltrates into the soil. Sandy soils will have larger **k** values than clay soils.

Tn   - Time from the start of Infiltration.

a   - Tn exponent. Represents the change in infiltration rate as the soil saturates with water. The value of **a** is between 0.0 and 1.0 (usually between 0.3 and 0.8). The larger **a**, the slower the infiltration rate changes as the soil absorbs water. Sandy soils will have larger **a** values than clay soils.

Modified Kostiakov Formula: $Zn = k * Tn^a + b * Tn + c$

See Kostiakov Formula above for Zn, k, Tn & a terminology.

b   - Constant infiltration rate.

c   - Immediate infiltration depth due to newly tilled or cracked soil. This represents water that quickly flows into air spaces in the soil.

Branch Function: $Zn = k * Tn^a + c$ prior to the Branch Time, Tb, then $Zn = Zb + b * Tn$

See Kostiakov Formula above for Zn, k, Tn & a terminology. See Modified Kostiakov Formula for definition of c.

Tb   - Branch Time; the time at which infiltration switches from a power curve ($Zn = k * Tn^a + c$) to a constant infiltration ($Zn = Zb + b * Tn$).

Zb   - Infiltration that occurred prior to time Tb.

b   - Constant infiltration rate after Branch Time

Infiltrated Depth

d(x) - Function describing the infiltrated depth along the length of a field.

Dapp - Average depth of applied water, or, applied volume expressed as an equivalent average depth.

> $Dapp = Dinf + Dro$ and sometimes approximately
> $Dapp = Dreq + Ddp + Dro$

Ddp - Average depth deep percolation, or, deep percolation volume expressed as an equivalent average depth.

Dinf - Average depth of infiltrated water, or, infiltrated volume expressed as an equivalent average depth.

> $Dinf = Dreq + Ddp$ (approximately)

Dlq - Low quarter average infiltrated depth = average depth for quarter of field receiving the least infiltrated depth (not necessarily contiguous).

> A function of d(x)

Dmin - Minimum infiltrated depth.

> Minimum of d(x)

Dreq - Required or target application depth.

Dro - Average depth of runoff, or, runoff volume expressed as an equivalent average depth.

Dz - Infiltrated depth contributing to the irrigation target

> $Dz = Dinf - Ddp$

Performance Measures

RO% - Runoff fraction

> $RO\% = Dro / Dapp$

DP% - Deep Percolation fraction

> $DP\% = Ddp / Dapp$

ADlq - Low-Quarter Adequacy

> $ADlq = Dlq / Dreq$

Admin - Minimum Adequacy

Admin = Dmin / Dreq

DUlq   - Low-Quarter Distribution Uniformity

DUlq = Dlq / Dinf

DUmin   - Minimum Distribution Uniformity

DUmin = Dmin / Dinf

AE   - Application Efficiency

AE = Dz / Dapp

PAElq   - Low-Quarter Potential Application Efficiency

*PAElq = DUlq * (1 - RO%)*

PAEmin   - Minimum Potential Application Efficiency

AE = Dz / Dapp

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