SPRINKMOD - Simulation of Pressure and Discharge Distributions in Pressurized Irrigation Systems: Graphical Interface and Strategy of Design

Camilo de Lelis Teixeira de Andrade and Richard G. Allen[1]

Abstract

SPRINKMOD is a computer model that simulates pressure and flow rate distributions along pipes and laterals of pressurized irrigation systems. The software runs in a WINDOWS® environment and simulates irrigation systems having multiple pump stations combined in series and/or in parallel, booster pump stations, parallel pipes and looping pipes in addition to more traditional, branched pressurized irrigation systems. Lateral types include hand-move, wheel line and center pivot laterals that may utilize pressure regulators and booster pumps. Leakage is included in the main pipe network and along the laterals and effects of plugged or worn nozzles are accounted for. Practically any type of nozzle and pump can be simulated since cubic spline functions are used to interpolate values from head-flow rate sets of data. Algorithms were developed and adapted to convert laterals into a single set of head-flow rate data so that a simplified algorithm can be used to solve the entire pipe network. A user-friendly interface is used to allow data for pumps, nozzle and pressure regulators to be interactively entered, edited and analyzed. The layout of the irrigation system is drawn on screen using the mouse.

Keywords: Design Programs, irrigation, sprinkler system hydraulics, Windows

Introduction

The first models for solving pipe hydraulic networks were developed for design and analysis of municipal water distribution systems due to the inherent complexity of these systems. These models used the Hardy-Cross method to solve the required equations. Other models use the Newton-Raphson method to solve the system of equations (Jeppson, 1990) or the linear theory method applied to flow rate in the pipes (Haestad, 1992) or to head at the network nodes (Walski et al., 1990). None of these models were designed to work directly with irrigation

[1] Irrigation Engineer Researcher, EMBRAPA (Brazil), Caixa Postal 151, 35701-970 - Sete Lagoas, MG, Brazil, camilo@cnpms.embrapa.br., Assoc. Prof., Biological and Irrigation Engineering, Utah State University, Logan, UT 84322-4105, allenric@cc.usu.edu.

systems, although some of them do allow for the inclusion of sprinkler heads at the ends of pipes (Jeppson, 1990). Models have been developed to design sprinkler laterals, taking into account economic aspects and details on local losses. Other design models simulate the whole irrigation system. Some models have graphical-based interfaces and can handle irrigation systems with irregular geometry and changes in elevation (Zazueta et al., 1989), but can not analyze systems having looping pipelines or multiple pumping stations.

The general objective of this study was to develop a computer model, SPRINKMOD, having an interactive graphical screen interface and capable of simulating pressure and discharge in complex pressurized irrigation systems comprised of looping pipelines, multiple pumping stations, pumps in parallel and/or series, booster pumps and any type of laterals including center pivots.

Hydraulic Principles

Many analytical computations in fluid mechanics are based on a relatively few fundamental principles. Most important among these are Newton's law of motion and the law of conservation of mass, energy and momentum. When applying the continuity equation to a junction of two or more pipes with steady incompressible fluid flow, the summation of flow rates coming to the junction is equal to the

$$\sum_{i=1}^{n_k}(Q_i)=0$$

summation of flows leaving the junction. Mathematically,
where,

$\sum Q$ = sum of all volumetric flow rates with proper sign
i = subscript for each flow joining the junction
n_k = number of links to the junction.

In terms of energy per unit of weight, the conservation of energy principle can be expressed as:

$$Z_1+\frac{P_1}{\gamma}+\frac{V_1^2}{2g}+h_m=Z_2+\frac{P_2}{\gamma}+\frac{V_2^2}{2g}+h_t$$

where subscripts 1 and 2 denote values at location one and two, and

Z	= elevation head	[L]
P/γ	= pressure head	[L]
$V^2/2g$	= velocity head	[L]
h_m	= head from pump or turbine	[L]
h_t	= total head loss between points 1 and 2.	[L]

The head loss term (h_t) in equation 2 includes friction (h_f) and local or minor (h_l) losses along the conduit. The most fundamentally sound method for computing friction losses, and the equation used in SPRINKMOD, is the Darcy-Weisbach

$$h_f = f \frac{L}{D} \frac{V^2}{2g}$$

equation, expressed as:
where,

h_f	= friction loss	[L]
f	= friction factor	[ ]
L	= pipe length	[L]
V	= average velocity	[L/T]
D	= pipe inside diameter	[L]
g	= acceleration due to gravity	[L/T^2]

The friction factor, f is dimensionless and can be roughly approximated as a function of Reynolds number and relative pipe roughness. The Churchill (1977) equation, which is valid over all Reynolds numbers is used for Reynolds numbers less than 5000. The Colebrook-White equation is used for higher Reynolds numbers due to its greater computational speed.

$$h_l = K_r \frac{V^2}{2g}$$

Local losses are expressed as:
where,

K_r	= local loss coefficient	[ ]

Pipe Network Components

Pipe networks are comprised of nodes and links, where links are elements that connect nodes. Links can be pipes, pumps or valves. Nodes are the junctions between links and are also points where demands, such as external flow, nozzle or irrigation laterals, can be defined. Reservoirs or tanks can function as nodes. The goal of pipe network analysis is to determine the pressure or total dynamic head at each node and the flow rate in each link for certain demands at the nodes.

Pipes comprise the major linking elements of networks. Assuming a pipe element with constant characteristics is linking node one to node two, after substituting the piezometric head ($P/\gamma + Z$) by H and including equations 3 and 4, the conservation of energy equation, 2, can be rewritten, provided the velocity is constant along the link:

$$H_1 - H_2 = (f\frac{L}{D} + K_r)\frac{V^2}{2g}$$

Equation 5 accounts for both friction and local losses along the pipe. Assuming a pump element is linking node one to node two, and substituting the piezometric

$$H_1 - H_2 = -h_p$$

head (P/γ + Z) by H, the conservation of energy equation 2 can be rewritten as: where h_p is the pumping head that includes effects of friction and local losses and velocity head changes, as well. The cubic spline function (Kincaid and Cheny, 1991) is used in place of polynomials to describe h_p so that any shape of pump curve can be accounted for.

A nozzle represents a demand point in a pipe network and is always associated with a node. The flow rate through a nozzle is a function of its inlet pressure. Nonflow control types of nozzles can be described with the orifice equation. However, many irrigation systems utilize flow control nozzles (FCN) that do not follow the orifice equation. Therefore, as for pumps, SPRINKMOD uses cubic spline interpolation to mathematically describe the relationship between flow rate and pressure for each nozzle. Leakage is represented by a set of data relating leakage flow rate to pressure. The function works like a nozzle, but the data have to be artificially generated by the user and will not necessarily follow any type of equation used for nozzles. The inclusion of nozzles and leakage into a pipe network analysis is done through a
simple expression:

$$Q_z = f(H_z)$$

where,

Q_z	= nozzle or leakage flow rate	[L^3/T]
H_z	= nozzle inlet piezometric head	[L]

A lateral is another type of demand point in a pipe network. A lateral is a feature mainly of pressurized irrigation systems and may have only one nozzle on it or as many as 200 nozzles such as in a center pivot lateral. It would be practically impossible to include equations for all pipes and nozzles on a lateral directly into the system of equations for a network analysis. Therefore, a technique is used to replace the multitude of nozzles along any lateral in a pipe network with a single set of lateral flow rate (Q_l) versus piezometric head (H_l) data points, as if the lateral were functioning as a large nozzle. An approach that is used is the one described by Meshkat and Warner (1985), where lateral inlet head and flow rate limits are defined so that all nozzles are operated over a range of possible pressures, which, in general, varies from zero to an upper limit found in nozzle catalogs. An iterative procedure along with a bisection method is used to determine the lateral inlet Q_l and H_l . In the current model spline interpolation is used to estimate Q_l as a function of H_l , in the same way as is done for nozzles placed directly in pipe network nodes. Laterals are included into the pipe network analysis using equation 7.

Pipe Network Solution

Solving a pipe network requires balancing all pressure sources available or generated in the network (pump stations, boosters) against all pressure "burning" elements such as pipes, elevation changes and pressure required to operate nozzles and/or laterals. This is accomplished by assembling and solving a system of equations. The simplest approach employed to solve looped pipe networks is the one that requires an equation for each of the unknown variables in the network, such as flow rate in pipes, nozzles, laterals and pumps, heads at nodes, heads generated by pumps, etc.. The advantage of this method is that it is very simple to apply and there is no need to define the topology of loops and pseudo-loops. In applying the continuity equation (1) to nodes with unknown piezometric head, one has:

$$\sum_{i=1}^{n_n}(Q_{n_i})+\sum_{i=1}^{n_p}(Q_{p_i})+Q_z+\sum_{i=1}^{n_l}(Q_{l_i})+Q_x=0$$

where,

Q_n	= pipe flow rate	$[L^3/T]$
Q_p	= pump flow rate	$[L^3/T]$
Q_z	= nozzle flow rate or leakage	$[L^3/T]$
Q_l	= lateral flow rate	$[L^3/T]$
Q_x	= external flow rate	$[L^3/T]$
n_n	= number of pipes connected to the node ($n_n \geq 2$)	[ ]
n_p	= number of pumps connected to the node($n_p \geq 1$)	[ ]
n_l	= number of laterals connected to the node ($n_l \geq 1$)	[ ]

Flows coming to a node have a positive sign, flows leaving the node take the negative sign. Eq. 9 is the first linear equation to be included in the system of equations required to solve the pipe network problem. Equations for pipes (5), pump stations (6) and nozzles and laterals (7) are also included into the systems of equations. Equations for pipes, pumps, nozzles and laterals are, in their original format, non-linear. Therefore it is not possible to apply methods to solve systems of linear equations directly in network problems. Either an iterative procedure or the linearization of the non-linear equations is required. The Newton-Raphson method is employed to solve the non-linear or implicit equations. In applying this solution technique, equations are modified so that their components add to zero when the solution is applied (Jeppson, 1977; Kincaid & Cheney, 1991). Numerical derivatives of equations were used in the model.

Model Description

Important features from pressurized irrigation system models and from water distribution system models were brought together into SPRINKMOD. The software package was written in Visual Basic for WINDOWS®, version 3.0. It runs in both Windows 3.11 and Windows 95.

Some of the features of SPRINKMOD are:

1. Laterals with inlet pressure control devices can be simulated, including center pivots;
2. Ground slope and water temperature can be varied for each pipe segment;
3. Pumps in a pump station can be combined in series and/or in parallel within the model (Andrade, Allen and Wells, 1998);
4. Booster pump stations can be placed in any part of the pipe network;
5. Networks with multiple sources of water or pump stations can be simulated;
6. Networks with pipes in parallel and with looping pipes can be simulated;
7. A user-friendly interface provides easy data entry and editing;
8. The layout of any pressurized irrigation system is drawn graphically on the screen and can be fully edited by using the mouse; node and link identification and association is done automatically by the software;
9. Data for the irrigation system components can be interactively entered and edited;

When SPRINKMOD is launched and the user provides the dimensions of the drawing area, the main screen is displayed (Fig. 1) which contains a drawing area, a menu bar and a ribbon bar. New projects can be drawn or existing SPRINKMOD projects can be edited or reviewed. Files can be created for pumps, pump stations, nozzles and pressure regulators. The layout of irrigation systems can be drawn, edited and simulated with results displayed and sent to a printer or a file.

Files for Pumps, Pump Stations, Nozzles and Pressure Regulators

Data files for pumps, pump stations, nozzles and pressure regulators need to be created before a simulation of an irrigation system can be run. Data for pump curves are entered using special forms, are graphically viewed, and a polynomial equation is fit to them. Data for nozzle and pressure regulators are entered through tables of head and flow rates for a specified number of data points. For both devices, a plot of the data can be viewed graphically so that outliers can be visually detected and corrected (Fig. 2). No equations are fitted to nozzle or pressure regulator data. Instead, cubic spline functions are used to interpolate intermediate values from the tables. Pressure regulators are devices used mostly in center pivot irrigation systems.

Drawing the Irrigation System Layout

SPRINKMOD allows the user to interactively draw and edit the irrigation system. The circles and lines used to represent the layout on screen (Fig. 1) are treated as independent graphical objects. The objects can detect mouse clicking and can generate an "event", so that each object can be identified and manipulated individually. A type structure array is created for each irrigation system component, including nodes, pipes, pump stations and laterals. The arrays hold graphical and some physical information describing each of the irrigation system components. The arrays are dynamically resized as components are added to or removed from the layout. In addition, arrays are updated every time the user changes the layout or data for a component. Each graphical element of the layout has a corresponding index in the arrays.

Data Entry, Error Trapping and Presentation of Results

Data entry seems to be one of the most tedious and error-prone parts of irrigation and water distribution system modeling. SPRINKMOD attempts to make this process as enjoyable and reliable as possible, as described earlier. In the case of pipes, data entered for one pipe can be duplicated to all downstream pipes to reduce data entry time. For laterals, data for one segment can be duplicated to all downstream segments. In addition, data for an entire lateral can be copied to other laterals. This strategy reduces the amount of time required for data entry and prevents many errors. Errors are trapped at several levels during data entry and simulation.

After the hydraulic solution is calculated, SPRINKMOD returns focus to the main screen interface where the simulation results can be viewed in tables. For laterals, detailed information is displayed for pipe segments, risers, pressure regulators (if any) and nozzles (Fig. 3). Project data and simulation results can be printed to a file for post processing and report generation or to the current selected WINDOWS printer.

Summary

SPRINKMOD provides a platform for straightforward and complete hydraulic analysis of pressurized irrigation systems, where pressure and flow rate regimes are simulated and reported for mainlines, manifolds and laterals. The operating point(s) for the system is determined by balancing the system hydraulics with pumping stations. Lateral types include handlines, wheellines, solid sets, linear moves and center pivots. Any type and layout of mainline designs, including loops and dual pipes can be simulated. The software presents a readily accessible means for determining operating characteristics and weaknesses of currently operating systems during system rehabilitation or diagnostics and for validating adequacy of proposed designs before construction. The Windows interface and graphical means for describing system layout brings the usage of the program into the hands of technicians and equipment suppliers.

Acknowledgments

We acknowledge the financial support provided to the first author by EMBRAPA - Brazilian Agricultural Research Corporation during his graduate studies at the Utah State University and support by the Utah Agricultural Experiment Station, UES 794.

References

1) Andrade, CLT, Allen, RG, Wells, RD (1998) PUMPCOM A simulation model for operating characteristics of pumping stations through combination of individual pumps. 7th Int. Conf. on Computers in Agriculture, Orlando, FL. (these proceedings).

2) Churchill, S.W. (1977). Friction-factor equation spans all fluid-flow regimes. *Am. Inst. Chemical Engineering J.* 23:91-92.

3) Haestad Methods (1992) Product catalog. Haestad Methods, Inc. Waterbury, Connecticut.

4) Jeppson RW (1977) Analysis of flow in pipe networks, Ann Arbor Science, Ann Arbor.

5) Jeppson RW (1990) Pipe network simulation analysis computer program-NETWK (vers. 3.1). User's Manual, Dept. Civil and Environ. Engineering, Utah State Univ., Logan.

6) Kincaid DR, Cheney EW (1991) Numerical analysis - mathematics of scientific computing. Brooks/Cole Publishing, Pacific Grove.

7) Meshkat M, Warner RC (1985) A user friendly interactive trickle irrigation design model. Proc. Third International Drip/Trickle Congress: Fresno, CA.

8) Walski TM, Gessler J, Sjostrom JW (1990) Water distribution systems: simulation and sizing, Lewis Publishers, Chelsea.

9) Zazueta FS, Smajstrla, AG, Haman, DZ (1989) Computer-aided design of landscape irrigation systems. Applied Agricultural Research 4:280

Figures

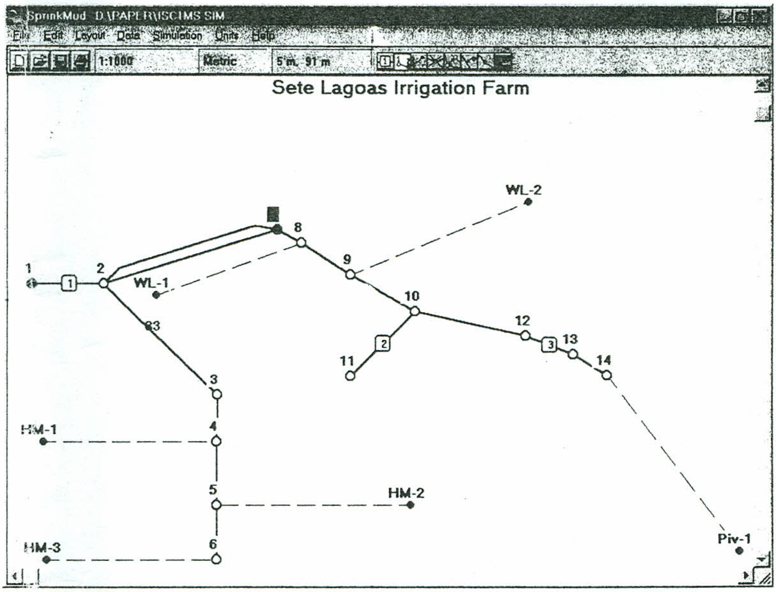

Figure 1. SPRINKMOD Main Screen Showing a System Layout Comprised of 3 Handline Laterals (HM), 2 Wheel line Laterals (WL), a Center Pivot (PIV-1), 3 pumping stations (in numbered boxes) and a Dual Mainline Segment (between nodes 2 and 7).

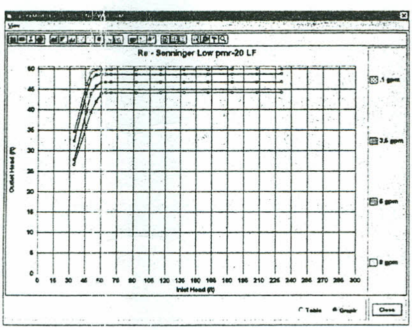

Figure 2. Part of Outlet Head Versus Inlet Head Displayed by SPRINKMOD for Different Pressure Regulator Flow Rates.

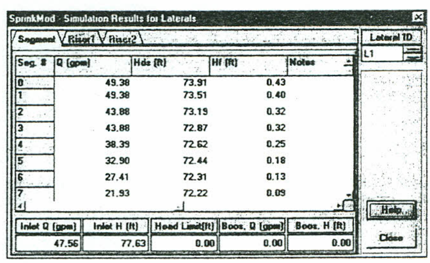

Figure 3. Segment Tab in the Dialog Box for Lateral Simulation Results (hds = head at downstream end of segment, hf = friction and minor loss in the segment).