Irrig Drainage Syst (2011) 25:265–278
DOI 10.1007/s10795-011-9123-0

Evaluation of surface irrigation system performance using System Dynamics (SD) approach

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Abstract Various methods and criteria have been proposed and utilized for the evaluation of irrigation systems performance, which can be used for comparison of design conditions and irrigation systems performance. Surface irrigation systems should be paid more attention among all other irrigation systems due to their operation simplicity and high losses. In the present study, while describing main relationships of irrigation evaluation criteria of application efficiency, water requirement efficiency, Deep Percolation Ratio and Tail Water Ratio, a method based on SD will be introduced. Modeling of this approach has been done using VENSIM-DSS software. Model has been tested in a case study that included the modeling of a furrow in four irrigation status: current situation, full irrigation, deficit irrigation and finally deficit irrigation with optimized irrigation cutoff time and inflow into furrow. The results reveal the high capabilities of SD approach in modeling water resources and irrigation systems. Its user friendly and ability in transferring data to the data bank can introduce this approach and software as an applicable decision support system.

Keywords Performance evaluation · Surface irrigation system · System dynamics · VENSIM-DSS

Introduction

It is essential to obtain 38% increase in agricultural products up to 2,025 in order to be able to supply world populations' demands (Seckler et al. 1999). Considering the increasing trend of population growth and as a consequence increase in people's demands in different sectors,

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especially in agriculture as the main water consumer, availability of systems for the evaluation of the performance of irrigation and drainage projects seems essential. The results of several scientific and research projects indicate that two parameters of water availability and getting water to the field can be introduced as the two most major criteria for the evaluation of water supply potentials (Tekrony et al. 2004).

Some researchers consider unavailability of sufficient high quality water and unavailability of water at the time of crop growth as the most major problems for irrigation activities, especially surface irrigation (Javan et al. 2002). Several parameters to evaluate performance of surface irrigation have been considered since 1990 (HSIAO et al. 2007; Burt et al. 1997).

Irrigation efficiency can be mentioned as the most important parameter for the desirability of an irrigation system performance. Improvement of water management in an agricultural project requires assessment and evaluation of the efficiency of an irrigation system. For the first time, Israelsen (1950) considered irrigation efficiency concept as the ratio of irrigation water consumed by crops to the water delivered to the district from various water resources. In 1993, a more perfect definition of irrigation efficiency was provided. According to the new definition, irrigation efficiency is a fraction of water delivered to the agricultural land used for crops consumption and or evaporated and referred to as consumptive use coefficient, C_{cu} (Jensen 1993).

In 1998, Molden mentioned nine indicators for the evaluation of an irrigation system performance; four indicators dealt with crop production, three relating to water supply capacity, and two relating to economic issues of an irrigation system (Molden et al. 1998a, b).

Making use of the mean of performance indicators for the assessment and evaluation of irrigation systems cannot fully analyze the variability in water use among farmers and or variation in management strategies among different crops in an agricultural district (Lorite et al. 2004b). Application efficiency, requirement efficiency, requirement distribution efficiency, and total distribution efficiency are among the most common parameters considered for the evaluation of the performance of a furrow irrigation system. Among the four aforementioned parameters, application efficiency and total distribution efficiency are more reliable comparing to the two other ones (Holzapfel et al. 2010).

Because of high costs of constructing and maintaining pressurized irrigation systems as well as difficulty in their operation, more attention is being given by researchers and users to optimized methods of furrow irrigation systems (Holzapfel and Arumi 2010). Although surface irrigation is easier in view of operation and application, optimized design and efficient management of these systems is rather complicated (Burguete et al. 2009b). Effects of excess irrigation, excess fertilizers and over-generation of wastewater indicate the necessity for the evaluation of such systems performance (Hadas et al. 1999; Asare et al. 2001). Several researches have provided methods for optimized and efficient design and also management strategies for the sustainability of a surface irrigation system (Khan et al. 2006; Hsiao et al. 2007).

Selection of a management approach or method for the implementation of an irrigation system depends on factors such as water availability, type of crop, soil characteristics, topography, and maintenance cost (Holzapfel and Arumi 2010). During the last two decades, since attaining methods for determining optimized design parameters, resources proper management, and minimization of disadvantages, surface irrigation has been assigned an increasing trend of application.

During the recent decade, several methods have been employed for the analysis of irrigation operations including analytical and numerical methods (Burguete et al. 2009a). Models employed for the calculation of water balance performance, indicators of irrigation systems, vary from one-dimensional models based on hydrological and physical concepts (Feddes 1998; Droogers and Kite 1999) to those simplified based on FAO calculation method (Dechmi et al. 2003). Performance of an irrigation system can be evaluated using field data of agricultural lands, farmers, and a simple simulation model (Lorite et al. 2004a).

For integrated evaluation of irrigation and water resources systems, giving serious consideration to the principles of hydrological modeling and mass balances in the analysis of system's general performance can have great influence on the accuracy of the evaluation results (Jensen 2007). Computer programs that use hydrological models can be useful for this purpose. These models vary from mathematical and statistical concepts to empirical and artificial intelligence ones (Doorenbos and Pruitt 1977; Allen et al. 1998). Some researches state that advance and recession curves as well as some indicators of determining the efficiency of a furrow irrigation system can be estimated with acceptable accuracy with the help of field data and also models based on spreadsheets instead of using complex mathematical and hydrological methods (Mateos and Oyonarte 2005).

In the recent years, extensive use has been made of concepts and tools such as remote sensing (RS) and geographical information system (GIS) in the preparation of accurate data and analyzing them in water sciences and agriculture (Hartkamp et al. 1999; Kite 2000; Kite and Droogers 2000).

According to Grigg (1996), real crisis in water management is a creeping crisis and changing in time (dynamic) that requires sustainable reactions and responses during different critical times. Researches and decision makers strongly advocate sustainable development as the optimal current and future approach to water related problems (Louks 2000). Using optimization abilities of SD approach and through determining the best combination of cultivation pattern, optimum use of water in an agricultural area can be achieved (Elmahdi et al. 2004).

In the modeling of surface irrigation system performance, because of various unknown parameters that are required to be estimated or calculated for achieving system performance indicator, evaluation error can indicate system situation different from that in reality. On the other hand, availability of multiple relations and also cause and effect concepts among dynamic variables (mainly have different values in each time step) makes it necessary to use SD approach.

Although the application of optimization techniques in water resources has attracted significant attention during the recent decades, verification of successful applications of these techniques in real world issues has not yet been proved, since, optimization techniques mainly use very simplified systems as their case studies. Hence, these systems cannot provide a perfect image of real systems (Yeh 1985; Simonovic and Fahmy 1999).

SD models for having feed-forward structures and for being object-oriented are considered as user friendly and practicable in different issues. Dynamic systems are based on system structure theory and a series of tools for demonstration of complex systems and analysis of system component dynamic behavior (Simonovic and Fahmy 1999). Being able to relate cause and effect relations among components of a complex system with logical relations and easily and clearly observe system's general reaction with the slightest changes that occur in the structure and quantity of each one of the components is considered as the strong capability of this approach. It can simply be stated that working in environments that use SD approach gives the modeler, stakeholders, and decision makers the power of sensitivity analysis with the highest possible level. The aim of this study is to describe and explain the capabilities of using SD approach in the evaluation of surface irrigation systems practicability and to identify the optimized irrigation cutoff time and inflow into the furrow.

Material and methods

In the continuation of this section, relations and criteria of the evaluation of irrigation system using SD approach will be explained.

Equations and criteria of surface irrigation system performance evaluation

For several reasons, objectives considered for an irrigation project can be different from reality. These can result from inaccurate system design or incorrect implementation of the system by contractors. In all cases, if the aim is quantitative display of inconformity of design situation with reality, then evaluation parameters of irrigation system performance can be used. For the description of a surface irrigation system performance four following parameters have been utilized:

1. Application Efficiency (E_a)
2. Deep Percolation Ratio (DPR)
3. Tail Water Ratio (TWR)
4. Water Requirement Efficiency (WRE)

In order to elaborate on the above parameters, Figs. 1 and 2 show water percolation curve for deficit and full irrigation. In these figures, X_L , length of furrow in meter, Z_{req} , water depth for supply of crop requirement in m^3/m, X_d , length of furrow where Z_{req} has been fully provided, in meter, V_{zd} , volume of water infiltrated in soil where irrigation is not completed, in m^3, and V_z is the volume of water infiltrated in soil from the beginning to the end of furrow, in m^3. Hence, considering the abovementioned concepts, relations of the four parameters used for evaluation of a surface irrigation system performance are calculated using the following equations:

$$E_a = 100\left[\frac{\left(Z_{req} \times X_d\right) + V_{zd}}{Q_{in} \times t_{co}}\right] \tag{1}$$

$$DPR = 100\left[\frac{V_z - \left(Z_{req} \times X_d\right) - V_{zd}}{Q_{in} \times t_{co}}\right] \tag{2}$$

$$WRE = 100\left[\frac{\left(Z_{req} \times X_d\right) + V_{zd}}{Z_{req} \times X_L}\right] \tag{3}$$

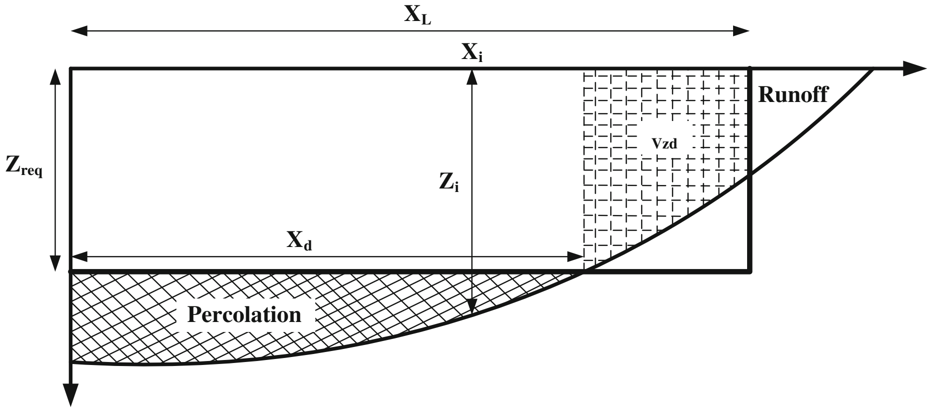


Fig. 1 Curve of infiltration depth for deficit irrigation

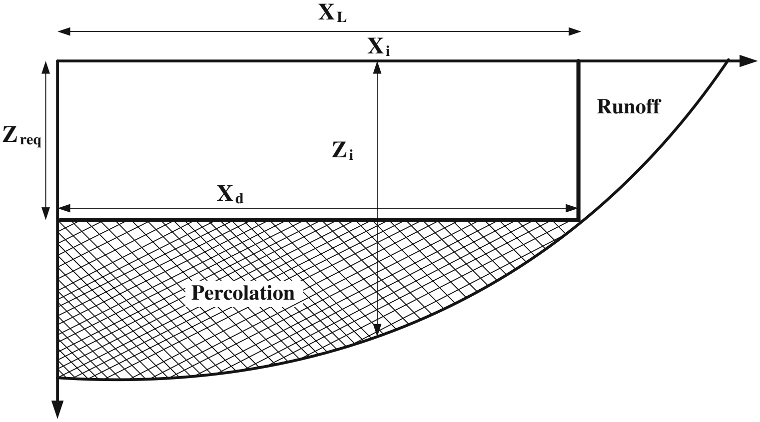


Fig. 2 Curve of infiltration depth for full irrigation (or excess irrigation)

$$TWR = 100 - E_a - DPR \tag{4}$$

Q_{in}, is inflow to furrow in m^3/min and t_{co} is irrigation cutoff time in minutes. For obtaining the profiles of Figs. 1 and 2, it is necessary to calculate water infiltration depth along the path of furrow. According to Kostiakov-Lewis' equation, water infiltration in soil can be obtained from the following equation:

$$Z = (K \times t^a) + (f_0 \times t) \tag{5}$$

In the above relation, Z , infiltration in soil in m^3/m, t , time from water advance step to water recession step for each place which Z is being calculated in minutes. a and k are coefficients calculated by Two-Point method using the following relations (Elliott and Walker 1982; Walker and Skogerboe 1987). f_0 , final speed of water infiltration in soil in m^3/min. $f_{0,}$ a and k can be calculated using the following relation:

$$f_0 = \frac{(Q_{in} - Q_{out})}{X_L} \tag{6}$$

Q_{out} is outflow from furrow in m^3/min.

$$a = \frac{Ln(V_L) - Ln(V_{0.5L})}{Ln(t_L) - Ln(t_{0.5L})} \tag{7}$$

$$k = \frac{V_L}{\sigma_z (t_L)^a} \tag{8}$$

$$V_L = \left(\frac{Q_{in} \times t_L}{X_L}\right) - (\sigma_y \times A_0) - \left(\frac{f_0 \times t_L}{1 + r}\right) \tag{9}$$

$$V_{0.5L} = \left(\frac{Q_{in} \times t_{0.5L}}{X_{0.5L}}\right) - (\sigma_y \times A_0) - \left(\frac{f_0 \times t_{0.5L}}{1 + r}\right) \tag{10}$$

$$\sigma_Z = \frac{a + r \times (1 - a) + 1}{(1 + a) \times (1 + r)} \tag{11}$$

$t_{0.5L}$ and t_L are in minutes and refers to the time that takes for water to reach the middle and end of furrow from the start point of inflow, respectively. $X_{0.5L}$, the half of the furrow length in meter. σ_y is the coefficient associated with flow shape on the soil surface to which a value between 0.7 and 0.8 can be assigned. A_0 is the wet section area of the beginning of furrow in m^2. r is the power parameter of water advance equation. Generally, water advance equation comparing to time can be viewed as an exponential relation as follows:

$$X = p \times t^r \tag{12}$$

X and t are the observed distance and time from the beginning point of furrow in meter and minutes, respectively. r and p are constant parameters of the equation. Several methods have been introduced to estimate such parameters. Here, the best estimation for these parameters would be extracted by optimization method available in VENSIM-DSS. In the next section, in addition to introduction of concepts of SD approach, it would be used in surface irrigation performance evaluation.

Introducing system dynamics model used in evaluations

In general, there are four components for describing and explaining a system using system dynamic approach as follows (Simonovic and Fahmy 1999):

1. Stock (levels): Indicates any variable with accumulative behavior such as volume of water infiltrating into soil.
2. Flow (rates): Indicates variables that increase or decrease Stock such as inflow to a furrow or outflow from a furrow.
3. Connector (arrows): Act as connectors among the variables in a system and indicate cause and effect relations among variables.
4. Converter: Converter of inlets to outlets in a system modeled using SD.

The best computer program known for SD modeling is VENSIM-DSS. Applications of this software have been proved in many modeling. Mention can be made of water resources river-basin planning and modeling (Simonovic 2000; Palmer et al. 1999), long-term water resource planning and policy analysis (Simonovic and Fahmy 1999), reservoir operation (Ahmed and Simonovic 2000) and as an optimizer in managing of irrigation demands (Elmahdi et al. 2004). Among the most important advantages of modeling water systems using SD and VENSIM-DSS program, mention can be made of the following:

- When the problem is involved with complex concepts and various variables in modeling, increasing variables or considered changes and situations can easily be applied in modeling (because this approach is object oriented)
- Ability to model quantitative and qualitative variables simultaneously.
- Due to dynamicity of the model, performance and use of the developed model with SD approach can be done in the easiest possible way
- Since comments and views can be stated and applied, each member of the modeling team, decision makers and stakeholders have the sense of ownership and participation in a model designed using SD approach
- Hypotheses and functions can be considered implicitly or explicitly
- For solving complex problems, the modeler does not need any high simplifications

- Due to simulation high speed, using different hypotheses, input data, and relations, the model can be trained and tested several times for obtaining the most actual situations
- Cost of computer software used in SD is low comparing to their efficiency
- Speed of compile and simulation implementation is very high
- Sensitivity analysis of the model is done easily and in the shortest possible time
- Ability to connect to data banks such as Excel which makes it possible for the model to receive import and export data results
- By applying and designing slider, can easily provide results of different scenarios and alternatives in a management and decision making modeling
- Has the ability to implement optimization method (linear & non-linear) in extracting constant coefficients.
- Due to fast simulation, connection to data bank, flexibility, and suitable demonstration of output results, VENSIM can be considered as an efficient decision support system.

The disadvantage of SD modeling can be merely the difficultly in programming for modeling with complex mathematical functions. For instance, programming of differential equations for oxygen dissolved in river flow path and or qualitative modeling for reservoirs are considered as equations that although solvable, create difficulties. Algorithm of decision support system for modeling evaluation of a surface irrigation system with SD approach using VENSIM-DSS can be illustrated as in Fig. 3.

In Fig. 4, applied relations and equations for evaluating surface irrigation systems are demonstrated. Optimization of advance curve parameters is done by variables and components which are separated by a rectangle box. At right part of Fig. 4, Eqs. 5–11 and left part

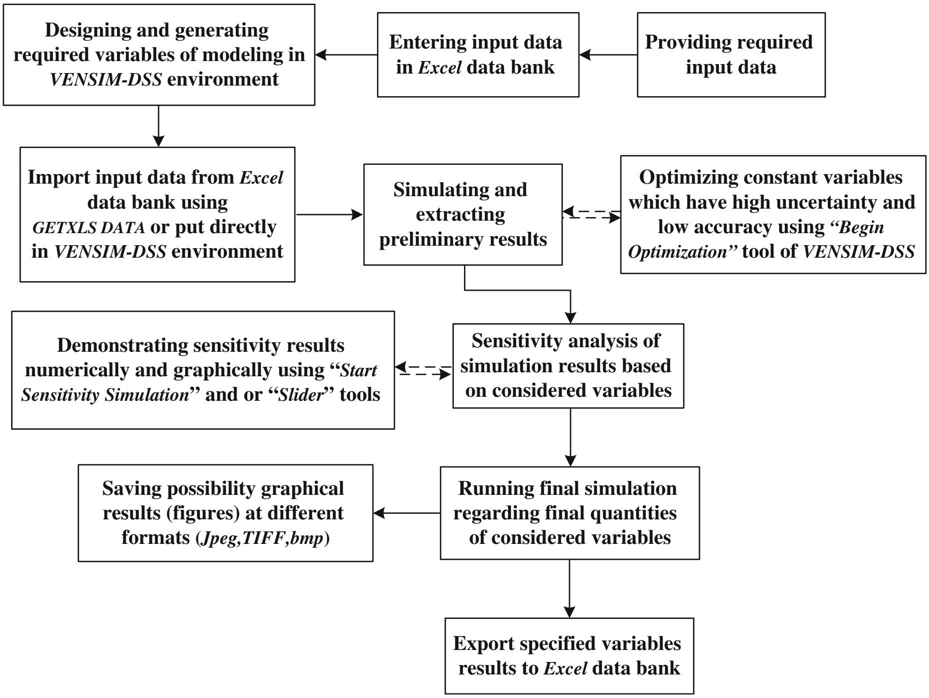


Fig. 3 Algorithm of decision support system for modeling evaluation of a surface irrigation system with SD approach using VENSIM-DSS

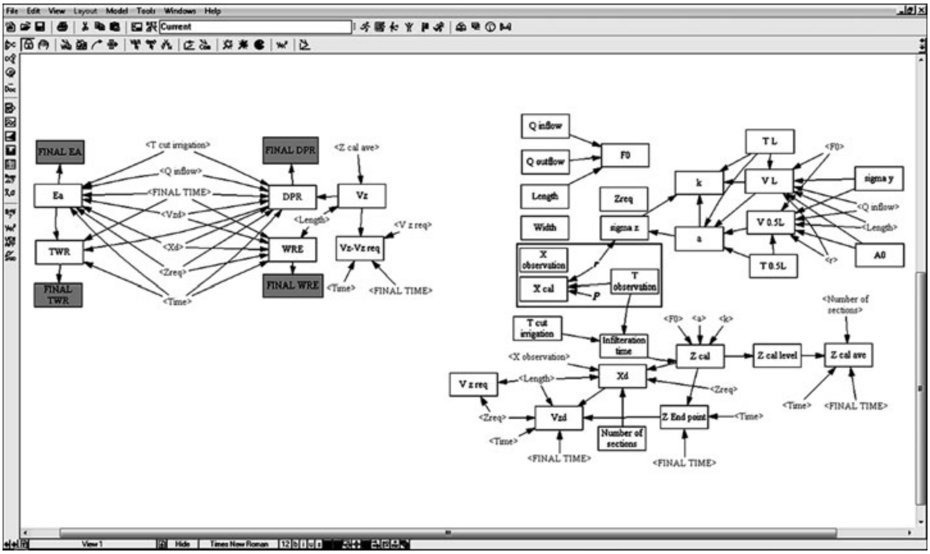


Fig. 4 Modeling sheet of evaluation of surface irrigation system with SD approach using VENSIM-DSS

of it, Eqs. 1–5 are modeled. In this figure, four evaluation criteria are colored with gray background to distinguish among other ones. Connection between variables of right and left parts of modeling sheet are made by connectors and shadow variables.

Case study, results and discussion

The case study considered is furrows with length of 165 m, width of 0.3 m and surface of 0.003 m^2 (at the beginning section of the furrow). Specifying sections have been performed with the distance of 10 m along the furrow and advance curve test has also been carried out. For obtaining advance curve, average inflow and outflow hydrograph discharge have been considered 1.5 and 0.5 lit/s, respectively. Crop and soil type of field are corn and loam respectively. Taking into account the plant root depth and existing relations for the calculation of crop required water depth, the value is assessed, 0.07 m^3/m. Since, the end of furrow is open, for calculating infiltration time; use has not been made of recession time. Furrow inflow and outflow hydrographs along with all the aforementioned information and data are saved in Excel data bank connected to VENSIM-DSS. Modeling will be done in the four following situations:

1. Irrigation in current situation (which apply excess water)
2. Deficit irrigation
3. Full irrigation
4. Irrigation with the application of optimization technique for inflow discharge into the furrow and irrigation cutoff time of water resources shortage

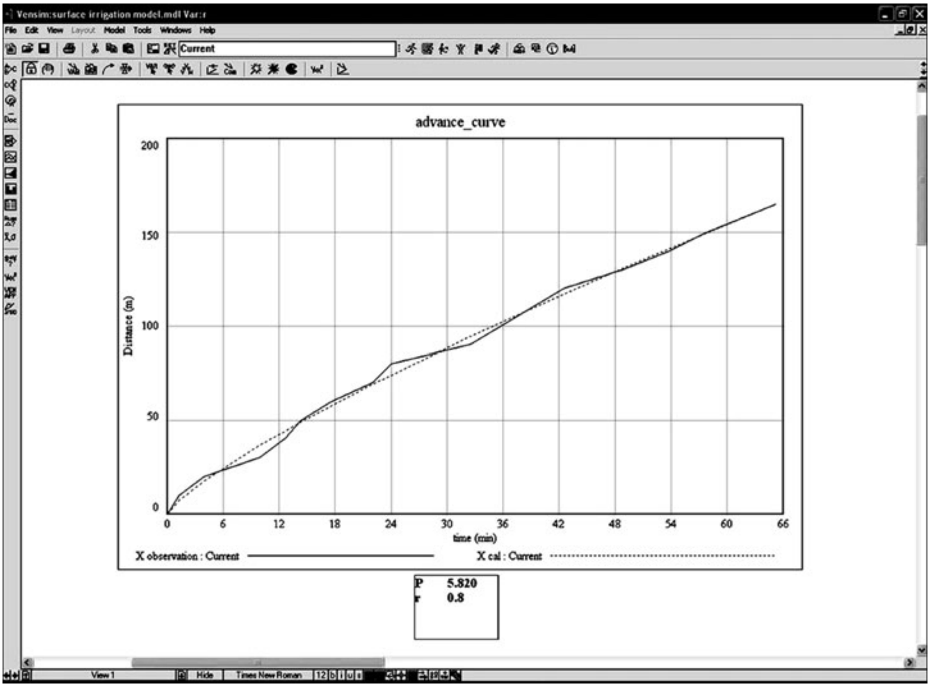
In the first situation, inflow and outflow discharge will be considered 1.5 and 0.5 lit/s, respectively and irrigation cutoff time will be regarded 150 min. In the second situation, inflow and outflow discharge will be the same as the first situation and irrigation cutoff time will be 100 min. As for the third situation, irrigation inflow and outflow discharge will again be the same as the first situation and irrigation cutoff time will be set in a way that the depth of infiltrated water at the end of furrow satisfy crop required water depth. This will be done using VENSIM-DSS sensitivity analysis. In other words, if there is sufficient water resources for irrigation purposes in a district then the most optimized situation for crop irrigation in a land would be full irrigation. In this situation, despite the increase in deep percolation and runoff loss comparing to the deficit irrigation, crop demands in the furrow would be fulfilled and plants would not experience water shortage stress.

For the fourth modeling situation in this study, water resources in the district are insufficient and thus amount of inflow discharge into the furrow as well as irrigation cutoff time would be set in a way that the two assessment criteria of WRE and Ea reach their maximum. Other two assessment criteria indicate degree of loss in the system which reach their minimum. Considering the above explanations, objective function of inflow discharge optimization and irrigation cutoff time for the fourth situation can be represented as follows:

$$Min\ Objective\ Function = (100 - E_a)^2 + (100 - WRE)^2 \tag{13}$$

Prior to continuing the modeling process, it is essential to calculate optimized amount of advance curve parameters. For this purpose, modeling has been done in VENSIM-DSS environment and using its optimization ability, by comparing observed measurements as well as the type of advance curve relation (Eq. 12), optimized value of r and p is calculated as 5.82 and 0.8, respectively. Observe curve and advance calculations considering optimized values of advance equation parameters are shown in Fig. 5.

Correlation coefficient (Corr) and root mean square error (RMSE) are supposed as parameters of goodness-of-fit to analyze the estimation accuracy of r and p. Values of Corr



P 5.820
r 0.8

Fig. 5 Observed and calculated advance curves to derive optimized parameters p and r

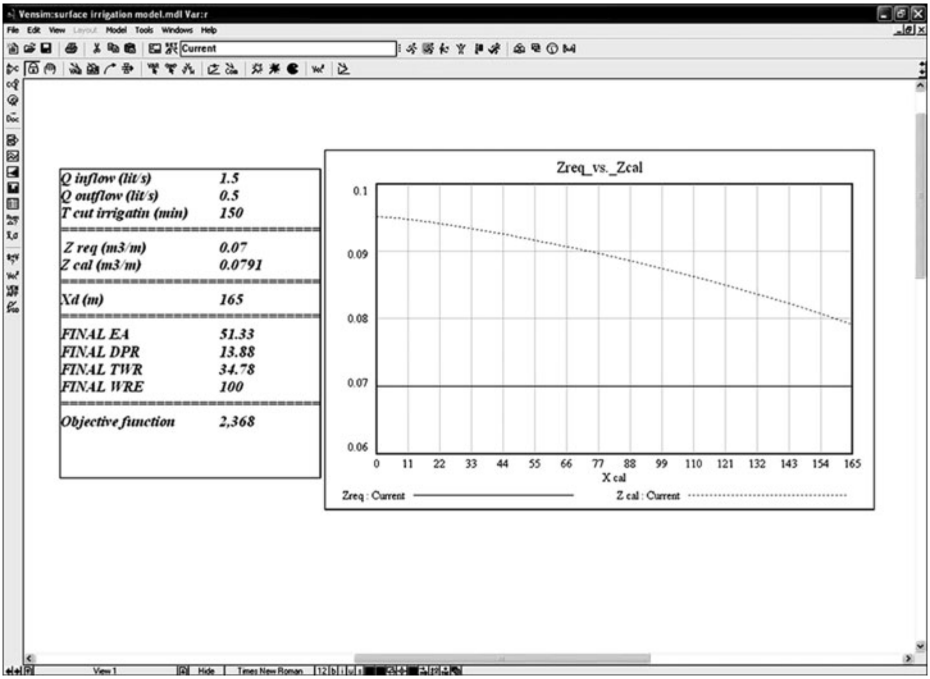
and RMSE are calculated 99% and 3.3, respectively, which indicates high accuracy of parameters estimation using VENSIM-DSS.

Final results of modeling for the four irrigation status are shown in Figs. 6, 7, 8 and 9. In these figures, dashed lines represent irrigation depth and solid lines indicate required water depth. Results of the four aforementioned modeling situations for system performance assessment indices are presented in Table 1.

Considering Fig. 6, irrigation current situation in the district indicates full irrigation. In this situation, depth of infiltrated water along the furrow exceeds crop water demand. Water infiltrated depth at the end section of the furrow is 0.0791 m^3/m that is more than the one required by crop (0.07 m^3/m). As can be expected, in full irrigation WRE index would be 100%, system's loss would be high and would leave the system in the form of deep percolation and runoff.

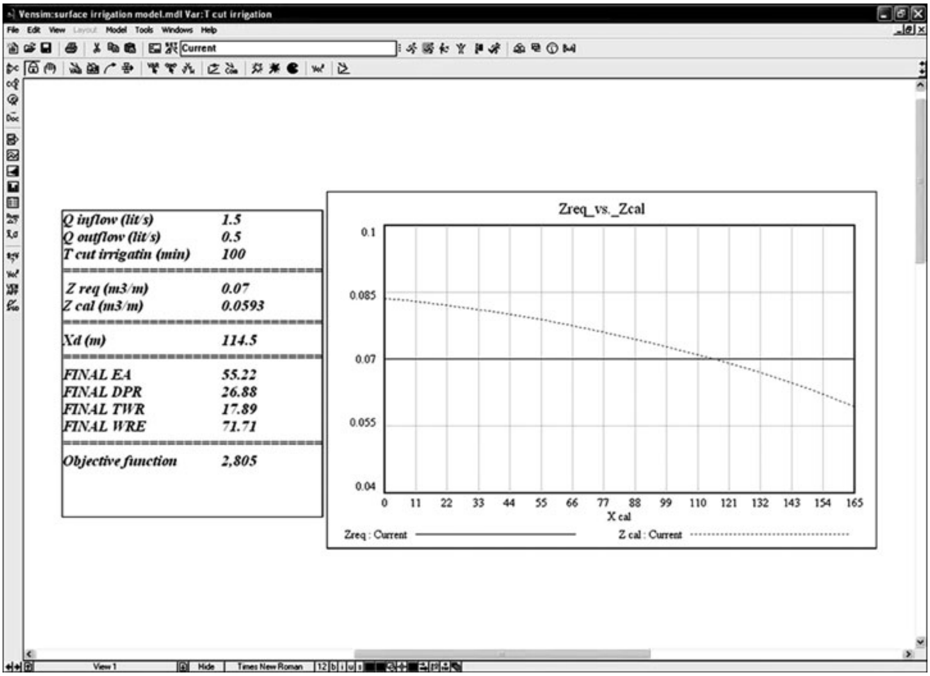
Figure 7 shows deficit irrigation situation. Here, end section of the furrow experiences water shortage stress. Beginning point of stress is estimated at 114.5 m from the furrow beginning. The greater distance from the beginning of the furrow the more stress would be experienced. At the end section of the furrow water infiltrated depth would be 0.0593 m^3/m, which indicates irrigation shortage of 0.011 m^3/m. In this situation, WRE would decrease to 71.71% and Ea would increase to 55.22%. Losses are less comparing to that of full irrigation situation.

Results of surface irrigation system assessment for full irrigation are shown in Fig. 8. These results reveal that if furrow inflow would be considered as 1.5 lit/s and irrigation cutoff time as 123.3 min then it can be expected that at the end section of furrow the depth of water infiltrated into soil would reach crop required water depth. In this situation, WRE index would be 100% as that in full irrigation situation and Ea index would reach 62.44%.



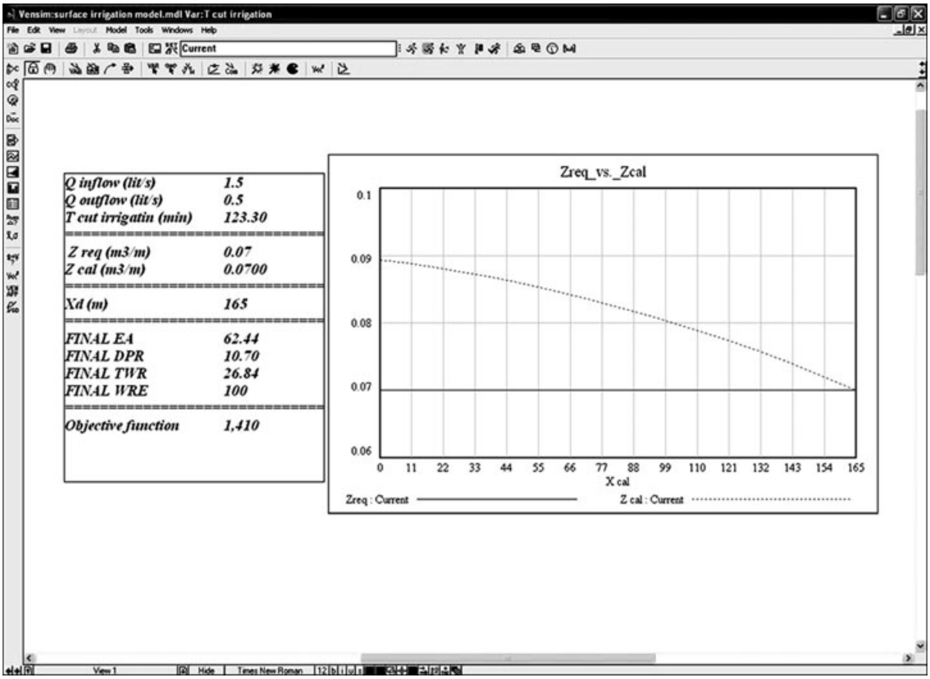
Q inflow (lit/s)	*1.5*
Q outflow (lit/s)	*0.5*
T cut irrigatin (min)	*150*
Z req (m3/m)	*0.07*
Z cal (m3/m)	*0.0791*
Xd (m)	*165*
FINAL EA	*51.33*
FINAL DPR	*13.88*
FINAL TWR	*34.78*
FINAL WRE	*100*
Objective function	*2,368*

Fig. 6 Evaluation results of surface irrigation system in current situation



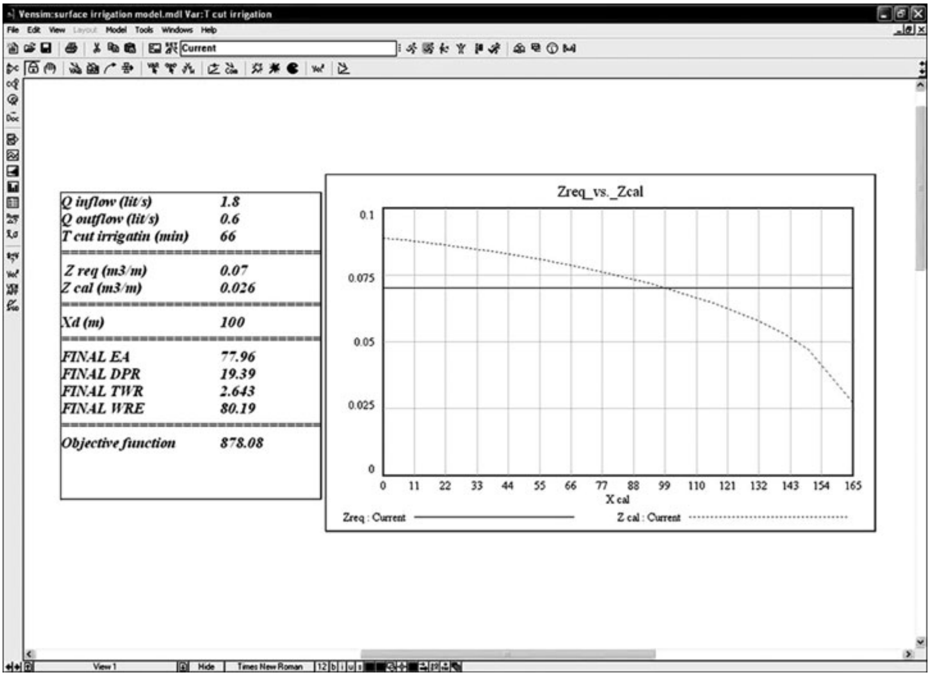
Q inflow (lit/s)	*1.5*
Q outflow (lit/s)	*0.5*
T cut irrigatin (min)	*100*
Z req (m3/m)	*0.07*
Z cal (m3/m)	*0.0593*
Xd (m)	*114.5*
FINAL EA	*55.22*
FINAL DPR	*26.88*
FINAL TWR	*17.89*
FINAL WRE	*71.71*
Objective function	*2,805*

Fig. 7 Evaluation results of surface irrigation system in situation of deficit irrigation



Q inflow (lit/s)	*1.5*
Q outflow (lit/s)	*0.5*
T cut irrigatin (min)	*123.30*
Z req (m3/m)	*0.07*
Z cal (m3/m)	*0.0700*
Xd (m)	*165*
FINAL EA	*62.44*
FINAL DPR	*10.70*
FINAL TWR	*26.84*
FINAL WRE	*100*
Objective function	*1,410*

Fig. 8 Evaluation results of surface irrigation system in situation of full irrigation



Q inflow (lit/s) 1.8
Q outflow (lit/s) 0.6
T cut irrigatin (min) 66

Z req (m3/m) 0.07
Z cal (m3/m) 0.026

Xd (m) 100

FINAL EA 77.96
FINAL DPR 19.39
FINAL TWR 2.643
FINAL WRE 80.19

Objective function 878.08

Fig. 9 Evaluation results of surface irrigation system in situation of optimized irrigation

Among the three above stated situations, highest irrigation application index will be assigned to full irrigation and the lowest loss is associated with deficit irrigation. Although value of DPR index for deficit irrigation situation is more than that of excess irrigation and full irrigation, however, it should be bore in mind that total volume of inflow to the furrow in deficit situation is less than that of the other two situations and hence with regard to the volume of infiltrated water as well as runoff loss, minimum loss is assigned to deficit irrigation.

As was mentioned earlier, the last modeling situation is associated with performing irrigation in a situation where there is water resources shortage. This situation is in fact a kind of deficit irrigation in which two main irrigation parameters i.e. furrow inflow and

Table 1 Evaluation Results of surface irrigation system performance in various status

	Irrigation in current situation	Deficit Irrigation	Full Irrigation	Irrigation with optimization
Q_{in} (m^3/min)	1.5	1.5	1.5	1.8
t_{co} (min)	150	100	123.3	66
X_d (m)	165	114.5	165	100
E_a	51.33	55.22	62.44	77.96
DPR	13.88	26.88	10.7	19.39
TWR	34.78	17.89	26.84	2.64
WRE	100	71.71	100	80.19
Objective Function	2,368	2,805	1,410	878

irrigation cutoff time will reach their optimized amount. Using optimization ability and VENSIM-DSS sensitivity analysis as well as introducing relation 13 as objective function, the most optimized value of inflow to the furrow and irrigation cutoff time are calculated as 1.8 lit/s and 66 min, respectively. Minimum value of objective function is 878, which indicates a meaningful difference comparing to other irrigation situations. Irrigation infiltration depth at the end section of furrow will be 0.026 m^3/m and water shortage stress will first occur at a distance of 100 m from the. Ea and WRE indices will be 77.96% and 80.19%, respectively and DPR and TWR loss indices will be 19.39% and 2.64%, respectively

Conclusion

In the present study, the importance of surface irrigation system accurate assessment was reviewed due to its ease of performance and high losses. All the relations associated with surface irrigation system assessment have been done using SD in VENSIM-DSS program. The reason for selecting this approach and program is their special capabilities in the modeling of complex systems with various variables and parameters. Rapid and accurate sensitivity analysis as well as capability in optimizing variables and parameters with fixed values makes it possible to decrease errors and uncertainty as much as possible during modeling process.

Modeling has been performed for four irrigation status: current situation, deficit irrigation, full irrigation, and deficit optimized situation. Results revealed that using the above mentioned capabilities, irrigation cutoff time can be decreased from 150 min in the current situation to 123.3 in the full irrigation situation. This time difference can prevent considerable amount of loss in a surface irrigation system in long periods. In situations where there is water resources shortage, existing resources can satisfy crop water requirements by optimizing inflow and irrigation cutoff time using ability of VENSIM-DSS. Making use of such methods in agricultural water management can prevent high losses of surface irrigation system as well as stress experienced by crop.

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