Surface irrigation simulation-optimization model based on meta-heuristic algorithms

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ABSTRACT

Simulation-optimization models are valuable tools for determining the optimal performance of systems. The main objective of this research was to develop and validate EDOSIM (Evaluation, Design, and Optimization of Surface Irrigation Model) as a simulation-optimization model for surface irrigation systems. For simulation, which consisted of the design or evaluation of basin, border and furrow irrigation, the Volume Balance model was used. For optimization, twenty meta-heuristic algorithms were applied. In this model, based on irrigation, the volume of infiltrated water to soil was calculated without having advance and recession data. The hydraulic objective function was used to minimize the linear combination of seven performance indicators. Regarding the optimization of the objective function, the functional, multi-dimensional, static, constraint, continuous, single-objective, and meta-heuristic optimizations were applied. Data obtained from fifteen experimental fields were used for the validation of simulation, algorithms parameters setting, and validation of optimization. Comparison of the simulation results of the EDOSIM model with those of the Hydrodynamic model of SIRMOD software showed the good performance of EDOSIM model and the proposed method for estimating the volume of infiltration with RMSE = 0.068, \( R^2 = 0.988 \), CRM = 0.005 and NRMSE = 4.2%. The Shuffled Complex Evolution (SCE) algorithm was found to be the best algorithm for the optimization of fields; in all fields, the objective function was decreased (improved). Comparison of the objective function of the EDOSIM model with eight solvers of Optimization and Global Optimization Toolboxes of MATLAB software also revealed the superiority of the EDOSIM model for optimization.

1. Introduction

About 90% of irrigated farms in the world are irrigated with surface irrigation. In surface irrigation, if deep percolation and runoff occur, the efficiency and uniformity of water distribution along the field will be decreased, resulting in low irrigation performance (Moravejalakhkami et al., 2012). Therefore, decreasing deep percolation and runoff are very important to improve the efficiency and uniformity of surface irrigation. For the design and evaluation of surface irrigation, deep percolation and runoff values are investigated using simulation models. However, due to the complexities of surface irrigation systems, simulation models are not able to determine the optimal solutions. Simulation-optimization models using mathematical calculation and objective function and constraints applied to the system can compensate for this disadvantage of simulation models (Mishra et al., 2005; Wu et al., 2016).

Abbreviations: \( t_a, t_{h}, t_{o} \), advance time to the end and one-half of the field length (min); \( t_{c}, t_{d}, t_{r}, t_{req} \), cut-off, depletion, recession, and the required intake opportunity time (min); \( E_i, E_f, E_r \), application efficiency, irrigation efficiency, requirement efficiency (%); \( D_1, D_2 \), distribution uniformity, distribution efficiency (%); \( TWR, DPR \), tail water ratio, deep percolation ratio (%); \( N_f, N_{fw} \), number of basins or borders, number of basins or borders along the field width; \( N_b, N_{bw} \), number of furrows, number of furrows along the field width; \( N_{ff}, N_{bf} \), number of furrows per set, number of sets; \( N_{y}, N_{by} \), number of basins or borders or sets of furrows along the field length, along the field width; \( V_L, z \), volume of infiltration (m\(^3\)), objective function; \( V_s, V_{0s}, L_s, u_s \), volume of water in advance time to the end and one-half of the length (m\(^3\)/m); \( Q_s, q_0 \), inlet discharge of furrow (m\(^3\)/min), per unit width of basin or border (m\(^3\)/min/m); \( q_{max}, Q_{max} \), maximum discharge of furrow (m\(^3\)/min) and per unit width of basin or border (m\(^3\)/min/m); \( Q_{min}, q_1 \), minimum discharge per unit width of border (m\(^3\)/min/m), system discharge (m\(^3\)/min); \( k, K \), coefficient of infiltration equation of basin or border (m/min), and furrow (m\(^3\)/min/m); \( f_0, F_0 \), basic intake rate of basin or border (m/min), and furrow (m\(^3\)/min/m); \( a, r, p \), exponent of infiltration equation, exponent, and coefficient of advance equation; \( T_{max}, T_{field} \), Base, \( Y_{max} \), top width, middle width, bottom width, and maximum depth of furrow (m); \( \alpha_i, \beta, \gamma, \gamma_i \), coefficients of equations of cross section, horizontal width, and wetted perimeter; \( C_i, C_0, p_i, p_0 \), cross section hydraulic parameters; \( A_0, Y_0 \), cross section at the inlet of furrow (m\(^2\)), depth at the inlet of basin and border (m); \( Z_0, Z_{L} \), leaching fraction, depth of leached water (m); \( L_f, L_x \), 0.5L, field length, length of basin, border or furrow, and one-half of the length (m); \( W_f, w, w_{0} \), field width, furrow spacing, and basin or border width (m); \( \Delta z_{req}, \Delta z_{req} \), Required infiltrated volume per unit length (m\(^3\)/m), root zone soil moisture deficit (m); \( n, \theta, \alpha \), Manning coefficient, maximum flow velocity (m/ min), slope (m/m); \( \gamma_{max}, \alpha_R, \) ART, maximum depth (m), subsurface shape factor, and advance and recession table

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Development of a simulation-optimization model for surface irrigation systems is carried out based on the initial performance of the system through the calculation of hydraulic performance indicators including application efficiency (Ea), irrigation efficiency (Ei), requirement efficiency (Er), distribution uniformity (DU), distribution efficiency (DE), tail water ratio (TWR) and deep percolation ratio (DRP) (Walker and Skogerboe, 1987), and selection of the appropriate optimization algorithm (Talbi, 2009). Initial optimization techniques such as Linear Programming (LP), Integer Programming (IP), Dynamic Programming (DP), and Nonlinear Programming (NLP) are time-consuming (Ramezani and Lotfi, 2013). Therefore, meta-heuristic methods have been developed to cover the drawbacks of the initial optimization techniques (Talbi, 2009). Also, with the expansion (Zhang and Li, 2007), improvement (Pham and Castellani, 2009), and hybridization (Ramezani and Lotfi, 2013) of the algorithms, their performance can be improved.

Many studies have been done to develop and use surface irrigation simulation models based on Hydrodynamic, Zero Inertia, Kinematic Wave, and Volume Balance models for the design and evaluation of surface irrigation methods (Ebrahimian and Liaghat, 2011). Some of them include the hydrodynamic models of IDIMOD (Fernández-Gómez et al., 2004) and SOFIP (Mailhol et al., 2005) that are used to simulate furrow irrigation; Zero Inertia model of ZIMOD is employed to simulate border and furrow irrigation (Abbasi et al., 2003), and SIDES model is also used to design and evaluate surface irrigation models (Adamala et al., 2014). Some types of software have also been developed to improve the design and operation of surface irrigation (Bautista et al., 2015; NRCS, 2004; Burguete et al., 2014). The mentioned models and software are not able to perform optimization; thus, hydraulic performance indicators are considered and calculated separately, where, the effectiveness of irrigation (Hart et al., 1979) depends on the simultaneous consideration of hydraulic performance indicators (Valipour and Montazar, 2012b).

Regarding the optimization of surface irrigation methods, researchers have used different models, algorithms, performance indicators, and decision variables. In the OPTIMEC model, to find the quasi-optimum combination of irrigation date, cut-off time and inflow rate, the Genetic Algorithm was used (Montesinos et al., 2001). In the WinSRFR surface irrigation model, for the optimization of length, width, and discharge, the trial and error method was used (Bautista et al., 2009a,b). In the SWDC model, for optimization of the discharge of furrow irrigation, five performance indicators were used (Valipour and Montazar, 2012a). In the POZAL model, to determine the optimal cut-off time, the Secant numerical method was employed (González et al., 2011).

Some examples of applied optimizations are optimization of the length and width of border irrigation based on the Zero Inertia model (Chen et al., 2013), automatic and synchronized optimization of furrow irrigation based on the estimation of the soil infiltration (Koech et al., 2014), the optimal design of the discharge and cut-off time of the closed-end furrow irrigation based on field data, WinSRFR model and Genetic Algorithm (Nie et al., 2014), using the one-dimensional version of Saint-Venant equations in open channels in the SISCO model (Gillies and Smith, 2015), analysis of the effect of inflow rates and durations on application efficiency and deep percolation of border irrigation with the WinSRFR model (Morris et al., 2015), and investigation of the improvement in application efficiency and distribution uniformity by changes in field layout within the current border irrigation (Anwar et al., 2016).

Many studies in different sciences have reported the ability of meta-heuristic algorithms and the superiority of simulation-optimization models in comparison to the simulation models. The lower (better) objective function of the HBMO meta-heuristic algorithm, in comparison with the traditional and gradient-based methods, in finding the shortest path of project management (Bozorg Haddad et al., 2010) has been mentioned; also, the lower (better) loss function of the ResOS simulation-optimization model, in comparison to the Standard Operating Policy (SOP), in reservoir operation (Jahanpour et al., 2014) has been previously reported.

There are few studies on the development of simulation-optimization models based on meta-heuristic algorithms for the design and evaluation of surface irrigation. Using these models is an idea to optimize the hydraulic performance of surface irrigation and to present an optimal strategy to simultaneously reduce deep percolation and runoff, and increase efficiency and uniformity. Also, there is a need to simultaneously consider performance indicators and decision variables and limitations for each decision variable. The objectives of this study were: 1) development of a simulation-optimization model for surface irrigation using the Volume Balance model and meta-heuristic algorithms (EDOSIM model), 2) validation of the simulation of the EDOSIM model based on the comparison of results with those of the Hydrodynamic model of the SIRMOD software by using different real sets of field data, and 3) validation of the optimization of the EDOSIM model through determining the best algorithms and comparing the optimal results with MATLAB software.

2. Materials and methods

2.1. Introduction of the EDOSIM model

In this research, a new simulation-optimization model called EDOSIM (Evaluation, Design and Optimization of Surface Irrigation Model) was developed for surface irrigation. In this model, for the simulation of the surface hydraulic flow, which consisted of the design and evaluation of basin, border and furrow irrigation, the Volume Balance model (Walker and Skogerboe, 1987) was used; regarding optimization, twenty meta-heuristic algorithms (Blum and Roli, 2003; Engelbrecht, 2007; Yang, 2010a,b) were applied (Fig. 1).

2.2. Simulation in the EDOSIM model

Hydraulic simulation of surface irrigation in the EDOSIM model was done using the Volume Balance equation (Lewis and Milne, 1938):

\[
\int_0^r Q(t)\,dt = \int_0^x A(x,t)\,dx + \int_0^x Z(x,t)\,dx
\]

(1)

Where, \( Q(t) \) is inlet discharge, and \( A(x,t) \) and \( Z(x,t) \) are the cross-sectional area of the surface and subsurface flow, which vary with distance \( x \), and time \( t \). To solve the Volume Balance equation, the numerical Power Advance method (Walker and Skogerboe, 1987) including the Kostiakov-Lewis infiltration \( (Z = k^t + f_i) \) and the Power Advance \( (x = pt^a) \) equations was used. Based on the assumptions of \( \kappa = 0.77A_0 \) and \( Q(t) = Q_0 \), Eq. (1) could be rearranged as follows (Elliott and Walker, 1982):

\[
Q_0t = 0.77A_0x + \sigma_kKt^x + \frac{F_0dx}{1 + r}
\]

(2)

Where, \( K \), \( a \) and \( F_0 \) are the parameters of Kostiakov-Lewis equation, \( r \) and \( p \) are the parameters of Power Advance equation, \( Q_0 \) is the inlet discharge, \( A_0 \) is the cross section at the inlet, and \( \sigma_k \) is the subsurface shape factor.

To calculate the volume of infiltration, when there is no advance and recession table (for the design, optimization of design, evaluation without advance and recession table, and optimization of evaluation), a method was proposed that was dependent on the irrigation method. In this method, auxiliary points of 0.25, 0.50, and 0.75 of the field length were considered and the length of field was divided into four equal sections.

For the design and evaluation of basin, infiltrations in 0.25, 0.50 and 0.75 of the field length \( (z_{0.25}, z_{0.50}, \text{and } z_{0.75}) \) were obtained from the linear interpolation between \( z_0 \) and \( z_t \) (Eq. (3)). For the design and
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