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Improved volume balance using upstream flow depth for advance time estimation

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ABSTRACT

Modification of classical volume balance models is one of the effective strategies to improving design of surface irrigation and optimal usage of water resources in agricultural section. In this paper, a modified volume balance model is developed to predict the advance curve in surface irrigation based on the variable actual depth at the upstream end of furrow. The simulations of the suggested structure are generated through a combination of different values of the furrow irrigation variables (inflow discharge, length of furrow, and infiltration parameters), to compare between different models and measured data. The results show that the modified volume balance is more accurate than previous equations by model efficiency of 0.94, 0.98, and 0.97 for furrow length of 60, 80, and 100 m, respectively. Sensitivity analysis is made by changing only one input parameter including discharge, field slope, roughness coefficient and infiltration parameters at a time while keeping all others fixed. Furthermore, the inflow rate can have a considerable impact on the model estimations. Nevertheless, the developed model is more sensitive to decreasing inflow discharge amount than to increasing it.

1. Introduction

The increasing population growth and rapid development in industry and agriculture has resulted to ever-increasing water demand for various purposes (Tabatabaei et al., 2010; Fakharinia et al., 2012; Lalehzari et al., 2014). Hence, developing countries will face water deficit crisis and have made huge investments for design and optimization of irrigation systems (Lalehzari et al., 2016). Surface irrigation covers about 90% of the total irrigated land in Iran. Hence, an accurate and suitable design of the surface irrigation systems can save more water and increase the irrigated land area (Ebrahimian and Liaghat, 2011; Lalehzari et al., 2015). Furrow method is widely used for irrigating pastures in Iran. Poor design and lack of suitable criteria for irrigation systems are generally responsible for uneven irrigation, leading to wastage of water, water-logging and salinity problems. There is considerable scope for reducing some of these losses through improvements in irrigation design, particularly the water application aspect. To design and improvement of irrigation efficiency, it is necessary to estimate the advance phase in furrow length.

A number of models are currently available for predicting advance and recession times of the water front down the furrow during an irrigation such as hydrodynamic model (Katopodes and Strelkoff, 1977); zero-inertia (Strelkoff and Katopodes, 1977) and kinematic wave (Walker and Humpherys, 1983). These times can be used to estimate distribution of infiltrated water, runoff at the end of furrow and the various indices for the evaluation of irrigation performance (Maheshwari, 1992).

1.1. Volume balance model

The volume balance is applied primarily onto the advance phase, and can be written for the border, basin, or furrow conditions. The first attempts at simulating the advance phase used volume balance models that apply the continuity equation over the entire flow profile and use simplifying assumptions to replace energy and momentum effects (McClymont, 2007). Volume balance is a simplified analytical solution of the hydrodynamic equations by neglecting the momentum equation in the Saint-Venant equations (Ebrahimian and Liaghat, 2011). The prediction of advance curve can be obtained by the volume balance approach in furrow using the following equation:

$$Q_o t_x = \int_0^x A(x,t)\mathrm{d}x + \int_0^z Z(x,t)\mathrm{d}x \quad (1)$$

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where Q_o is the flow rate at the inlet boundary; t_x is the advance time; $A(x, t)$ is the cross-sectional area of the surface flow, variable with distance (x) and time (t); $Z(x, t)$ is the cross-sectional area of the infiltrated water, variable with distance and time.

Evaluation and modification of volume balance model have been widely studied to estimating the advance and recession phases of furrow irrigation (Hart et al., 1968; Levien and Souza, 1987; Al-Azba and Strelkoff, 1994; Al-Azba, 1999; Valiantzas, 1999; Golestani et al., 2010).

Lewis and Milne (1938) derived an integral equation for advance time in terms of inflow, mean surface water depth and cumulative infiltration. Philip and Farrell (1964) later used Laplace transforms to simplify the integral equation for different infiltration equations. Hall (1956) applied a numerical scheme over a sequence of time-steps where normal depth at the upstream end was assumed along with a power-law shape factor for solving the volume-balance equations. Another modified advance curve was approximated by Strelkoff (1977) using a simple surface shape profile, and assuming normal depth at key points along the surface. This technique was modified by Levien and Souza (1987), using a power function to represent furrow geometry and a simple Kostiakov function to represent infiltration (McClymont, 2007).

In this paper a modified volume balance model is developed to predict the advance time in furrow irrigation. In the suggested method, the upstream surface water depth is actual depth and variable in time.

2. Materials and methods

2.1. Model description

Valiantzas (1994) develops a model for computing the advance distance in borders. The proposed model uses a volume-balance equation, with an adjusted surface shape factor in conjunction with the zero-inertia motion equation evaluated at the head of the border. The results show the programming requirements and computation time of the suggested method were significantly less compared with other sophisticated methods. Valiantzas (1994) assumes the following equation could be used to estimate surface depth profile:

$$y(x,t) = y(t)\left(1 - \frac{x}{s(t)}\right)^b \tag{2}$$

where t is the time; x is the distance from the beginning; $y(x,t)$ is the water surface depth; $y(t)$ is the water surface depth at the upstream end; $s(t)$ is the advance position for time t; and b is the constant with $0 < b < 1$. Valiantzas (1994) propose the following empirical relationship to approximate b:

$$b = \frac{0.45}{(1+P)^{0.2}} \tag{3}$$

where the parameter P can be written as the relative of normal depth, bed slope and infiltration coefficients.

$$P = \frac{\left(q_o S_o \left(y_n/k\right)^{1/a}\right)}{y_n^2} \tag{4}$$

The surface storage v_{sur} within the time step t can be estimated by integration over a set of advance increments, Δx, at each constant time steps (Eqs. (2) and (4)).

$$v_{\text{sur}} = \int_0^{s(t)} y(t)\left(1 - \frac{x}{s(t)}\right)^b \mathrm{d}x \tag{5}$$

$$v_{\text{sur}} = \frac{y(t)}{(s(t))^b} \times \left.\frac{(s(t)-x)^{b+1}}{(1+b)}\right|_{x=0}^{x=s(t)} \tag{6}$$

In upstream end of furrow, $x = 0$, Eq. (6) can be written as

$$\Delta v_{\text{sur}} = \frac{(y_i s_i - y_{i-1} s_{i-1})}{(1+b)} \tag{7}$$

Golestani et al. (2010) use the modified discharge per unit width and Eq. (7) to approximate surface storage in furrow irrigation. According to Hall (1956), the volume of infiltrated water can be approximates for the each distance increment located between s_{i-1} and s_i as given by (Fig. 1)

$$\Delta v_{\text{sub}} = \sum_{k=1}^{i-1}\left(\frac{(z_{i-k+1} - z_{i-k-1})\Delta s_k}{2}\right) + I_1(s_i - s_{i-1}) \tag{8}$$

$$z = kt^a + f_o t \tag{9}$$

$$I = \sigma_{z1} kt^a + \sigma_{z2} f_o t \tag{10}$$

where z is the cumulative infiltration per unit furrow length, that is predicted using Kostiakov–Lewis function, k and a are empirical parameters, f_o is the final infiltration and σ_{z1}, σ_{z2} are subsurface shape factors. Hence, the volume balance equation is as follow:

$$q_o \Delta t_i = \Delta v_{\text{sur}\cdot i} + \Delta v_{\text{sub}\cdot i} \tag{11}$$

Original volume balance is based on the assumption of normal flow depth at the upstream end. The objective of the study was to adjust the above functions for furrow design, based on the assumption of the actual depth at the upstream end and volume balance equation (ADVB). Then the adjusted equations are used to estimate the advance distance. The proposed solution was compared to the four improved volume balance models by Fok and Bishop (1965), Walker and Skogerboe (1987), Zandparsa and Sepaskhah (1991), Valiantzas (1994) and with results from measured filed data. Advance distance at a sequence of time steps can be obtained by combining Eqs. (7), (8) and (11) as:

$$s_i = \frac{C}{y_i + (1+b)I_1} \tag{12}$$

$$C = q_o \Delta t(1+b) + y_{i-1}s_{i-1} + (1+b)I_1 s_{i-1} - (1+b)\sum_{k=1}^{i-1}\left(\frac{(z_{i-k+1} - z_{i-k-1})\Delta s_k}{2}\right) \tag{13}$$

In Eq. (12), y_i is an unknown parameter which is defined as flow depth at the beginning section of the furrow in time step i. Fok and Bishop (1965) considered y_i constant and assumed it to equal normal depth, y_n. Advance equation is estimated as a function of normal depth computed via the Manning equation:

$$s_i = \frac{q_o t}{\sigma_y y_n + \sigma_{z1} kt^a + \sigma_{z2} f_o t} \tag{14}$$

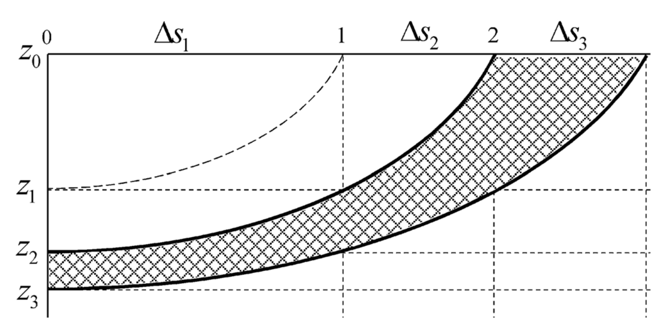

Fig. 1. Schematic layout of infiltrated water presented by Hall (1956).