Surface irrigation simulation models: a review

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Abstract: This paper reviews the literature and results of more than one hundred published articles in scientific journals with respect to simulation of surface irrigation. The results showed that 53.4% of the simulations belong to furrow systems. It is 35.9% for border systems and 10.7% for basin irrigation. However, satisfactory simulations were 70.3%, 63.6%, and 54.5% for border, basin, and furrow systems, respectively. The priority of irrigation methods to simulate using hydrodynamic (HD) and other models is border, basin, and furrow irrigation. It is border, furrow, and basin for kinematic wave (KW) and volume balance (VB) models. Finally, this priority is basin, border, and furrow for zero inertia (ZI) model. Meanwhile, the models estimated advance and infiltration phases better than recession and runoff phases during an irrigation event.

Keywords: assumption; irrigation; modelling; Saint-Venant; simplification.

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1 Introduction

Nowadays irrigation plays a major role in hydrological cycle and accurate knowledge about its phases can help for scheduling and forecasting in water resources management (Banihabib et al., 2012; Rahimi et al., 2015; Valipour, 2014a, 2014b, 2014c, 2014d, 2015; Valipour et al., 2015). There are four different models to simulate surface irrigation events including full hydrodynamic (HD), zero inertia (ZI), kinematic wave (KW) and volume balance (VB). The HD equations used in the mathematical models for describing the overland flow in surface irrigation are the equations of mass and momentum conservation, known as the Saint-Venant equations (Chow, 1959; Strelkoff, 1969). These equations, after the modification to include infiltration, are

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}+\frac{\partial Z}{\partial \tau}=0 \tag{1}$$

$$\frac{1}{Ag}\frac{\partial Q}{\partial t}+\frac{1Q}{A^2 g}\frac{\partial q}{\partial x}+\left(1-\frac{Q^2 T}{A^3 g}\right)\frac{\partial T}{\partial x}-S_0+S_f=0 \tag{2}$$

where y is depth of flow (m), t is time from the beginning of irrigation (s), τ is intake opportunity time (s), Q is discharge (CMS), x is discharge along the field length (m), Z is infiltration rate (m s^{-1}), g is gravity acceleration (m s^{-2}), S_0 is longitudinal slope of the field (m m^{-1}), S_f is slope of energy grade line (m m^{-1}), A is cross sectional area (m^2), and T is top with of flow (m).

1.1 HD model

The most complex and accurate is the HD numerical simulation model, which uses the full form of the Saint-Venant equations, i.e., both equations of mass and momentum conservation. These models, if properly implemented, should provide simulations that are more accurate over a wide range of field conditions when compared to the other mathematical models. Due to their accuracy, they are often used for the calibration and evaluation of simpler models (Ebrahimian and Liaghat, 2011).

1.2 ZI model

The ZI models are a simplified form of the HD model without the acceleration and inertia terms. Strelkoff and Katopodes (1977) simplified the HD equations by neglecting the inertial terms in the Saint-Venant equations. If the inertia terms are neglected, equation (2) becomes

$$\frac{\partial y}{\partial x} = S_0 - S_f \tag{3}$$

1.3 KW model

The depth gradient of the flow and inertial terms of the momentum equation [equation (2)] are often small in comparison with those of the bottom and friction slopes. Therefore, equation (2) can be further simplified by assuming that the depth gradient and inertial terms are negligible and thus becomes (Ebrahimian and Liaghat, 2011)

$$S_0 = S_f \tag{4}$$

1.4 VB model

The VB is applied primarily onto the advance phase, and can be written for the border, basin, or furrow conditions. As the solution of HD equations is possible only with the numerical techniques using computers, some early studies on surface irrigation modelling focused on providing analytical solutions of the flow problem. The momentum equation was therefore completely neglected. The models based on this simplification were called volume-balance models and are based on the principle of mass conservation and on the assumption of normal flow depth at the upstream end. Water-front advance can be predicted by the VB approach in border and furrow using the following equation (Ebrahimian and Liaghat, 2011):

$$Q_0 t_x = \int A(x,t)dx + \int Z(x,t)dx \tag{5}$$

where Q_0 is flow rate at the inlet boundary, t_x is time of advance, $A(x, t)$ is cross sectional area of the surface flow, variable with distance (x) and time (t), and $Z(x, t)$ is cross sectional area of the infiltrated water, variable with distance and time.

2 Review of the previous researches

Simulation of surface irrigation using mathematical models has been studied in many studies. In this section, a review has been done (based on a time sorting from 1980s to 2014) on the most important results obtained according to their focuses on only furrow irrigation, only border irrigation, only basin irrigation, or a comprehensive study (more than one irrigation method). In each part, only results of the more important studies have been presented and similar works have not been cited.

2.1 Application of the models in furrow irrigation

The KW analysis should be a satisfactory tool to predict water advance, intake, and runoff for sloped furrow irrigated systems (Walker and Humpherys, 1983). Holzapfel et al. (1984) compared the HD, ZI, KW, and VB models to predict advance and recession phases in furrow irrigation. Excellent prediction of the advance and recession phases was obtained with the HD, ZI, and KW models. Yitayew et al. (1985) studied factors affecting uniformity and optimal water management with furrow irrigation using a KW mathematical model. The study shows economically optimal water management for furrow irrigation can be obtained with proper balance between changes in the input variables and runoff and to some extent deep percolation. Izuno and Podmore (1986) used the KW model for surge irrigation management in furrow systems. Simulation model results indicated that there appears to be an optimum number of surge cycles to complete the advance phase to irrigate uniformly using a desired volume of water. Rayej and Wallender (1987) compared the VB and KW models to simulate advance and runoff phases in furrow irrigation. The cumulative model predicted more accurately than the incremental model when compared to field data and the KW model results. Wilson and Elliott (1988) compared the ZI and VB models to predict advance phase in furrow irrigation. The VB method performed poorly on those runs with relatively low infiltration rates that gradually approached steady-state infiltration. Singh and He (1988) evaluated Muskingum model (The VB approach) for prediction of advance and recession phases in furrow irrigation. The Muskingum model can simulate advance, storage, and vertical and horizontal recession phases satisfactorily. Rayej and Wallender (1988) evaluated the KW model for predicting advance, recession, and runoff phases in furrow irrigation. Simulated advance using the time solution model was consistent with field data as well as with the results of the space solution model of Walker and Humpherys (1983). Recession time, however, was consistently over-predicted. Simulated advance was relatively insensitive to space step for Kimberly data. Advance, uniformity, and average infiltration were all estimated more accurately using a spatially varying infiltration function, compared to a uniform infiltration function. Walker and Busman (1990) estimated infiltration parameters of furrow using the KW model. The results indicate that infiltration parameters can be estimated with sufficient accuracy from early advance data to allow an accurate forecast of efficiency and uniformity at the end of the irrigation. Wallender and Yokokura (1991) solved the KW model for furrow irrigation by time iteration successfully. Ranjha et al. (1992) presented the best management of pesticide-furrow irrigation systems. A KW model was used to estimate water infiltration for alternative furrow lengths and inflow rates. For a given furrow length and inflow rate, pesticides with higher partition coefficients and shorter half lives have a lower potential for groundwater contamination (less leaching) than otherwise. Bautista and Wallender (1992) developed a HD model that solves for time of advance as a function of distance. Comparison of simulation results with different space and time step combinations indicate that the consequent loss of accuracy is relatively small. The method used to compute infiltration as a function of wetted perimeter may aggravate the loss of precision in the computations. Schmitz and Seus (1992) developed a ZI model for irrigation advance in furrows (ZIFA). ZIFA was first favourably compared to the outcome of a HD model. Then, together with a numerical ZI model, it was applied to simulate field experiments, where it showed excellent agreement with the observed data as compared to the complex numerical solution. The cumbersome mass-balance techniques, which together with assumptions on the water surface profile are used to describe the flow in the tip region of the advancing wave, can be replaced by ZIFA. Fonteh and Podmore (1993) presented a physically-based infiltration model for furrow irrigation. The models were associated with a KW furrow irrigation model in which infiltration could vary spatially or be constant. The predicted irrigation performance of the KW model with various infiltration models indicated that these simple models predict furrow infiltration satisfactorily in fine textured soils and are suitable for practical use. However, all the models over predicted the total volume of outflow. Mailhol and Gonzalez (1993) introduced furrow irrigation model for real-time applications on cracking soils using the KW and VB approaches. This model can be used for prediction and analysis of irrigation water use efficiency by monitoring the advance phase on one furrow. Bautista and Wallender (1993) identified furrow intake parameters from advance times and rates using the HD model successfully. Fonteh and Podmore (1994) applied geostatistics to characterise spatial variability of infiltration in furrow irrigation using the KW model. The effect of the level of precision in the estimation of infiltration on the performance parameters of the irrigation was most significant on the distribution uniformity. Reddy and Singh (1994) modelled the KW equations, analysed its error, and compared with the ZI model for furrow irrigation systems successfully. Tabuada et al. (1995) modelled furrow irrigation using the HD method. Although the amount of computer time was a practical limitation of the model, it is possible to improve it either by increasing the time step, to simulate infiltration, or by using another method to solve the Richards' equation. McClymont and Smith (1996) optimised furrow irrigation advance data using the VB model. Initial testing of the model indicated that it is indeed a useful tool for determining the infiltration characteristic. Renault and Wallender (1996) evaluated initial inflow variation impacts on furrow irrigation using the VB model. The authors concluded that the advance phase is perturbed by a non-step flow at the beginning of the process, and this influences the infiltration evaluation procedure when limited to the advance phase. Raghuwanshi and Wallender (1996) investigated modelling seasonal furrow irrigation using the VB method. The model was used to predict irrigation performance for each irrigation event during the season, soil moisture before each irrigation, seasonal evapotranspiration (ET), and bean yield along the furrow at 10-m intervals. Application of the models for advance and infiltration phases was better than the recession phase. Zerihun et al. (1996) analysed sensitivity of performance parameters in furrow irrigation using the ZI model. The advance time and distribution uniformity had the most and the least sensitivity to input parameters, respectively. Camacho et al. (1997) presented a model for management and control of furrow irrigation in real time using the KW approach. The authors mentioned that an overestimation of soil infiltration is obtained if average infiltration is used in a furrow irrigation model. Raghuwanshi and Wallender (1998) optimised furrow irrigation schedules, designs and net return to water using the KW model. The net return to water increased, and the seasonal inflow, losses, and bean yield decreased in the case of variable interval scheduling as compared to the fixed interval scheduling. Upadhyaya and Raghuwanshi (1999) presented a semiempirical infiltration equation for furrow irrigation systems using the VB model. The semiempirical equation for cumulative infiltration correlated to the measured cumulative infiltration very well for both the calibration and the prediction data set. Valiantzas (2000) introduced a surface water storage independent equation for predicting furrow irrigation advance using the VB model and compared it with the KW model. For furrows in which the surface storage is relatively important, the proposed equation predicts advance with good accuracy, whereas previous models ignoring the surface storage greatly over predict the advance rate. Valiantzas et al. (2001) estimated furrow infiltration from time to a single advance point using the VB model. By placing total reliance on a single advance point, the method only works well if that advance point is accurate and lies on the power curve that is representative of the whole advance. In the other study, a particularly simple equation is developed to explicitly calculate the time of advance in surface irrigation. The suggested equation is also compared with observed furrow data and with the ZI model. In all the cases examined, the proposed equation provided predictions that were in good agreement with field data and the ZI model results in advance and infiltration phases (Valiantzas, 2001). Esfandiari and Maheshwari (2001) evaluated furrow irrigation models including the HD, ZI and KW. It was found that the HD and ZI models performed best in predicting advance times and the ZI and KW models performed best in predicting recession times. The KW approach of the Walker model is not suitable for simulation of irrigation events on furrows with slopes up to 0.1%. Latif and Mahmood (2004) simulated advance rates for continuous and surge irrigated furrows. Results simulated by the KW model revealed that the water front advance curves matched closely with the observed ones in most surge treatments. Wohling et al. (2004) analysed physically-based modelling of interacting surface-subsurface flow during furrow irrigation advance using the ZI method. The comparison between laboratory results and the numerical irrigation model showed that simulated irrigation advance times of run one and three compared favourably with the experimental data, as was the case for the subsurface flow phenomena. However, the results of run two indicated that soil cracking, due to a relatively high clay content combined with a relatively long drying period prior to this irrigation experiment, had a considerable impact on the infiltration process. Eldeiry et al. (2005) designed a furrow irrigation system for clay soils in arid regions. A VB model was applied to simulate water flow in the furrow system, and the results were compared to those obtained from the field measurements. This study showed that a VB model can be satisfactorily applied to clay soils, and the length of the furrow and its inlet inflow are the main factors affecting application efficiency. However, the use of short furrow lengths with low furrow inflows is not recommended for clay soils given the sensitivity these systems have to furrow length and inflow. Walker (2005) calibrated furrow infiltration and roughness using a stepwise multilevel scheme. The multilevel approach to formulating estimates of intake and roughness parameters was a substantial simplification over other methodologies. Bakker et al. (2006) studied application efficiencies and furrow infiltration functions of irrigations in sugar cane using the ZI model. It was determined that gains of up to 20% can be achieved in the irrigation application efficiency compared to the current situation. Gillies et al. (2007) surveyed accounting for temporal inflow variation in the inverse solution for infiltration in furrow irrigation. The proposed technique remains restricted by limitations similar to that of other VB models but offers greater performance under typical inflow variations often experienced in practice. Khatri and Smith (2007) proposed a simple real-time control system based on the VB model for furrow irrigation. The simulation results showed that the system is feasible. Nasseri et al. (2008) investigated effectual components on furrow infiltration. Large spatial variability observed at field scale showed that infiltration is affected not only by the factors out of the soil but also by the soil properties within the soil profile. Mailapalli et al. (2009) introduced a physically-based model for simulating flow in furrow irrigation using the ZI model. The model development will be extended to simulate sediment, nutrient and pesticide transport in spatial and temporal scales for predicting the impact of irrigation management on environment. Saha et al. (2009) modified Horton's equation to model advance phase in furrow irrigation systems using the VB approach. The simulation studies indicated that cumulative infiltration can be enhanced by increasing the inflow rate at the head of the furrow. Holzapfel et al. (2010) evaluated furrow irrigation management and design criteria using efficiency parameters and simulation models using the VB model successfully. Mohamed et al. (2010) developed a Muskingum-Cunge routing model for design of furrow irrigation using the VB approach and compared it with the ZI model. Performance of the model was satisfactory for advance phase and no satisfactory for recession phase. Valipour and Montazar (2012a, 2012b, 2012c) and Valipour (2012, 2013) compared the HD, ZI and KW models to optimise infiltration parameters in furrow irrigation systems. The author concluded that performance of the HD and ZI was similar and better than the KW model in all irrigation events. Soroush et al. (2013) simulated advance, recession, and runoff phases of furrow irrigation using the slow-change/slow-flow equation and compared it with the ZI and KW models. The proposed model can provide a suitable and simple numerical simulation tool for design and evaluation of furrow irrigation for all bottom slopes and boundary conditions.

2.2 Application of the models in border irrigation

Singh (1980) derived shape factors for border irrigation advance using VB model. He concluded that irrigation advance length is sensitive to infiltration constants. It is desirable to estimate these constants accurately, preferably from physically measurable border characteristics. Ram and Singh (1982) compared the VB (Wu model, Strelkoff model and Singh-McCann model) and KW (Sherman-Singh model) approaches for evaluation of horizontal recession in border irrigation. Among all models for determination of the time of horizontal recession, the Sherman-Singh model predicted recession time most closely. In order of accuracy of predictions on the basis of average absolute percentage deviation, the Sherman-Singh model was followed by the Strelkoff model, Singh-McCann model and the Wu model. Similarly, in order of sensitivity to infiltration, these models can be ranked as the Sherman-Singh, Strelkoff, Wu and Singh-McCann models. Singh and Ram (1983) verified a KW model for border irrigation by experimental data. For the data analysed the KW model was found to be sufficiently accurate for modelling the entire irrigation cycle except for the vertical recession. Ram et al. (1986) presented a quasi-steady state integral model for closed-end border irrigation. The calculated advance times were found to be consistently smaller than observed values. Jaynes (1986) used a simple model for border irrigation simulation. The model solves the differential form of the combined equations for the conservation of mass and momentum with the acceleration terms removed. Model results compare well with measured advance and recession times. Predicted ponding depths during infiltration and total water infiltrated over the border also agree well with observed behaviour. The model gives results equivalent to those of other existing the HD and ZI models but is much simpler to program and requires less computer code. Singh and Yu (1987) presented a mathematical model for border irrigation simulation. The proposed model was found to be superior in terms of accuracy (to predicted advance and recession phases), ease of application, and physical basis of parameters. Singh et al. (1988)

investigated Muskingum model (the VB approach) for simulating advance and recession phases in border irrigation. The Muskingum border irrigation model predicted both advance and recession phases satisfactorily for the data analysed. Yu and Singh (1989) applied the VB method to simulate all irrigation events in border systems. The results showed that the proposed model predicts the advance distances and horizontal recession times more accurately. Meanwhile, the model may not be adequate for level (or zero-slope) borders. Singh and Yu (1989) employed the VB model for simulation of advance, recession, and infiltration phases in closed-border irrigation system. The vertical recession did not fit level borders or borders with a very small slope. The proposed model will not fit for field soils that have large infiltration rates. Jain and Singh (1989) studied border systems by the KW model successfully. The authors claimed that the scheme was adequate to model the entire irrigation cycle for the data analysed and can be applied to any other data. Katopodes et al. (1990) estimated surface irrigation parameters for advance and infiltration phases using the ZI method successfully. Schmitz and Seus (1990) evaluated a ZI model of border irrigation advance (ZIMBA). It was used to simulate extant field experiments. The outcome of ZIMBA was always very close to the observed data and to the outcome of a HD numerical model. Maheshwari et al. (1990) studied sensitive analysis of parameters of border irrigation models. The models were sensitive to a varying degree to the field parameters; the sensitivity of individual parameters being dependent upon the phase of irrigation, i.e., advance or recession, and to some extent on the model used. Maheshwari (1992) surveyed effects of recession criteria on prediction of recession times in border irrigation by the HD, ZI and approaches. The prediction of the models for a given recession criterion varied considerably with the events and indicated that other factors affecting flows in border irrigation should also be taken into account while selecting a recession criterion. Hume (1993) determined infiltration characteristics by the VB for border check irrigation. Under dry soils conditions the form of the infiltration characteristic is wrongly predicted leading to an overestimate in the amount of infiltration. Katopodes (1994) studied hydrodynamics of surface irrigation using the HD and ZI models. He showed that application of the models was satisfactory in advance phase. Austin and Prendergast (1997) presented an analytical KW model of border irrigation that incorporates the linear infiltration function and compared it with HD and ZI models. The fact that the analytical solution does not require a computer, so is not subject to numerical instabilities, means that it has the potential for incorporation in electronic irrigation timing devices and, ultimately, in whole-farm irrigation automation systems. Dholakia et al. (1998) simulated border irrigation system using explicit MacCormack finite difference method using the HD, ZI and KW models. The HD model was found to be more suitable for simulation of all the four phases of border irrigation events. Alazba (2002) introduced a simple mathematical model for water advance determination in border irrigation by combination of the ZI and VB model. The model is applicable to conditions under which the traditional VB model fails. Douglas et al. (2010) presented an integrated model for simulation of border irrigated dairy pasture production systems. Model predictions agreed well with data reported in the literature for annual irrigation amounts and pasture growth. A limitation of the integrated model was its dependence on two sets of infiltration models that were difficult to relate to each other. Zhang et al. (2011) proposed a one-dimensional HD model of border irrigation based on a hybrid numerical method. The proposed model of border irrigation can increase computational stability and convergence, can improve computational precision and efficiency, and can provide a good numerical simulation tool for the design and evaluation of border irrigation systems. Raghuwanshi et al. (2011) investigated infiltration evaluation strategy for border irrigation management using the VB model. The methodology presented in their work has the potential for use in real-time management of border irrigation systems. Weibo et al. (2012) estimated infiltration parameters and manning roughness in border irrigation using the VB model. The maximum average absolute error was 6.07% for water advance in all border tests. The results showed that this method is reliable for estimating infiltration parameters together with Manning roughness, and the water advance trajectory is not sensitive to Manning roughness. Dong et al. (2013) presented a hybrid coupled model of surface and subsurface flow for surface irrigation using the HD method. Compared with the iterative coupling strategy usually implemented in the existing coupled models, the proposed hybrid coupling strategy exhibits better simulation accuracy and lower total VB error. Chen et al. (2013) evaluated potential of improving border irrigation performance through border dimensions optimisation using the ZI and KW models. The performance of optimised border irrigation systems was greatly improved in advance and infiltration phases with simulation models and field tests. Mahdizadeh Khasraghi et al. (2014) simulated open- and closed-end border irrigation systems and claimed that although the HD model uses the Saint-Venant equations without simplification, during numerical solution of them by computer, uncertainty is raised due to further calculations than the ZI and KW models.

2.3 Application of the models in basin irrigation

Guardo (1995) used the VB model for simulating advance phase in basin irrigation. The fact that the Manning roughness coefficients obtained by matching the depth of the water at the inlet for the final advance were in general agreement with the condition of the vegetation at the time of data collection indicates that this model may provide a means to estimate reasonable values of hydraulic resistance (Manning's n) for different kinds of soil and vegetation if sufficient advance data are available. Guardo et al. (2000) compared the ZI and VB models for basin irrigation systems. Errors in the estimation of the time of advance between the ZI and VB models range from 3.87 to 8.44% from unit inflows ranging from 2.0 to 7.0 L s^{-1} m^{-1}. In addition, the ZI model yields smaller average flow velocity for the entire basin than for the VB model. Bradford and Katopodes (2001) presented a finite volume model for prediction of advance and infiltration phases in basin irrigation. The model's efficiency is due to the use of explicit time integration, which does not require the inversion of large matrices as do implicit schemes. Khanna and Malano (2006) reviewed modelling of basin irrigation systems with respect to the HD and ZI approaches. It was concluded that two-dimensional rather than one-dimensional models are required to simulate all the flow processes involved in irrigation events in basin systems due to the nonlinear nature of flow over the basin. Kang et al. (2009) identified two-dimensional characteristics of surface water hydraulics in an irrigated paddy field using the HD model. Model simulations revealed that the initial ponding depth affects the wave propagation and the increase in water depth during irrigation. Gonzalez et al. (2011) assessed basin irrigation design with longitudinal slope using the HD and ZI models. Practical recommendation would be to consider giving the optimised slope to the field when levelling this field, considering also the negative impacts of land levelling. Zhang et al. (2014a) analysed two-dimensional surface water flow simulation of basin irrigation with anisotropic roughness using the HD model. The results showed that with basin surface anisotropic roughness, the proposed model can successfully simulate water flow in advance and recession phases of basin irrigation. Zhang et al. (2014b) in another research proposed two-dimensional ZI model of surface water flow for basin irrigation based on the standard scalar parabolic type. The computational efficiency of the constructed ZI model is approximately 17 times of the HD model of basin irrigation.

2.4 Comparative studies

Turbak and Morel-Seytoux (1988a, 1988b) applied the KW and VB models for simulation of all irrigation events in border and basin systems. The constant infiltration rate model does not seem to be a good tool for calculating the advance times, the opportunity times, or the final infiltrated depths. This is caused by the underestimation of the advance times. The model's predictions of recession times were generally acceptable because during recession the infiltration rate would have probably reached a constant value. But the opportunity times will still be high compared to field values. The model estimated the final volumes of infiltration and runoff reasonably well. How useful the model is will be determined by the objective at hand. The use of the infiltrometer data in the constant infiltration rate model resulted in low estimates of infiltration. Mohamoud (1992) evaluated Manning's roughness coefficients for tilled soils using the KW model. The hydrograph analysis method determines meaningful Manning's roughness coefficients and infiltration rate parameter values as evidenced by the results of the KW equation. Gharbi et al. (1993) evaluated effect of flow fluctuations on free draining, sloping furrow and border irrigation systems using the HD, ZI and KW models. All the results show that the KW model has the capability to predict different phases of border irrigation as long as the lower end boundary conditions are free draining and the field has a slope of at least 0.1%. Sakkas et al. (1994) employed the HD model to simulate all of irrigation phases in border and furrow irrigation. Results were satisfactory. Feyen and Zerihun (1999) assessed performance of border and furrow irrigation systems and the relationship between performance indicators and system variables using the VB model. The authors concluded that performance of border and furrow irrigation systems and the relationship between performance indicators and system variables. Abbasi et al. (2003) evaluated various border and furrow irrigation numerical simulation models including the HD, ZI and KW. All models used in the comparative analysis predicted the advance and recession times and the infiltrated and runoff volumes satisfactory. Walker and Kasilingam (2004) corrected the VB equation for shape factors during advance in border and furrow irrigation. Hori et al. (2008) estimated field irrigation water demand based on the KW model considering soil moisture balance. Ebrahimian et al. (2010) evaluated various quick methods for estimating furrow and border infiltration parameters. Using the VB equation and estimated infiltration parameters, the total infiltrated volume and advance times were predicted to evaluate the accuracy of estimated infiltration parameters. The results showed that the performance of the Elliot and Walker method would be improved using binomial approximation instead of Kiefer approximation. Ebrahimian and Liaghat (2011) evaluated the HD, ZI and KW models for furrow and border irrigation systems. The results indicated that the performance of all models was satisfactory for the prediction of the advance and recession times. The HD, ZI and KW models predicted the recession times better than the advance times. The predicted advance and recession times were estimated by these models more accurately than the infiltrated and runoff volumes. Also the accuracy of these models for the prediction of the advance and recession times was better for the experimental furrows in comparison with the experimental borders.

3 Summing up

To discuss about performance of the models, comparison of the results of the previous studies is essential. In this section, all of the figures were plotted based on the outputs of the papers mentioned in the previous sections. In the other word, the percentages shown in the figures were obtained based on the results of the previous sections.

Figure 1(a) shows tendency of researchers to use surface irrigation simulation models in different irrigation methods. The furrow irrigation method was simulated more than the border and basin methods using surface irrigation simulation models. The low percent of basin irrigation underlines other results about this method should be considered with precaution. Figure 1(b) shows tendency of researchers to use surface irrigation simulation models. Although the HD is the most precise model, the KW model was applied more than other surface irrigation simulation models due to its simplifications and less time to run by computers. The KW model is simpler than the HD and ZI models as well as it is more accurate than the VB model. Therefore, the most irrigation methods are simulated using the KW model. Figure 1(c) shows percent of irrigation phases simulated using surface irrigation simulation models. The advance phase was estimated more than the other phases and the infiltration phase was in the second place. It is note that some of irrigation methods are close-end and they do not produce runoff. Figure 1(d) shows satisfactory simulations for different irrigation methods. The 'satisfactory' in this paper means all previous studies (mentioned in the paper) that their authors simulated irrigation methods and irrigation phases with an acceptable price (deduced according to the authors' opinion of each paper) based on error indices used and their expert opinion. Although furrow irrigation was simulated more than other methods, the results indicate that success of surface irrigation simulation models for furrow systems is less than basin and border irrigations. Figure 1(e) shows satisfactory simulations using surface irrigation simulation models. The other models estimated different phases of irrigation event as well as simulated irrigation methods better than conventional models. Why? Because they were adopted for specific conditions related to those studies. Therefore, they applied Saint-Venant equations with suitable simplifications to better simulation of surface irrigation (decreasing error indices). However, they are limited and do not recommend for other conditions. In addition, although the HD model simulated surface irrigation better than the ZI, KW and VB models, the results of the HD, ZI and KW were close together and therefore, the ZI and KW models can be used when a very high accuracy is not considered. Figure 1(f) shows satisfactory simulations for irrigation phases. Performance of surface irrigation simulation models to estimate advance phase is better than other phases.

Figure 1 (a) Tendency of researchers to use surface irrigation simulation models in different irrigation methods (b) Tendency of researchers to use surface irrigation simulation models (c) Percent of irrigation phases simulated using surface irrigation simulation models (d) Satisfactory simulations for different irrigation methods (e) Satisfactory simulations using surface irrigation simulation models (f) Satisfactory simulations for irrigation phases Satisfactory simulations for irrigation phases (see online version for colours)

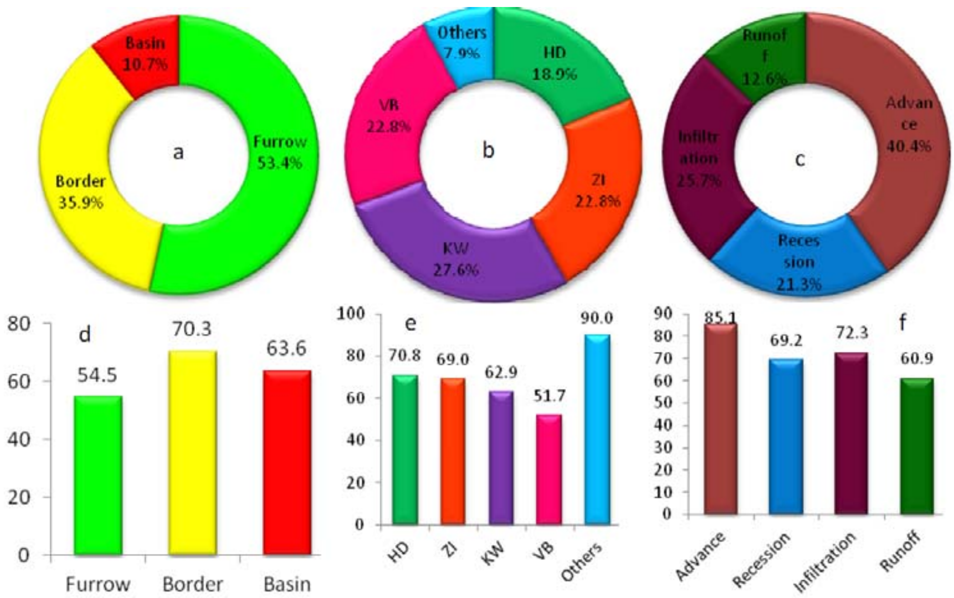


Figure 2(a) shows satisfactory simulations of surface irrigation simulation models in furrow irrigation. According to Figure 1(b), the ZI and KW models were applied for simulation of surface irrigation more than HD model. Therefore, it is a reason that they simulated irrigation events better than the HD model [Figure 1(b)]. Figure 2(b) shows satisfactory simulations of irrigation phases in furrow irrigation. In furrow systems, the recession phase is estimated with less accuracy than the other phases. This is due to nature of furrow irrigation and superior of horizontal infiltration (intake) than vertical infiltration in this system. Figure 2(c) shows satisfactory simulations surface irrigation simulation models in border irrigation. As expected, performance of the HD model is better than the ZI, KW and VB models. Figure 2(d) shows satisfactory simulations of irrigation phases in border irrigation. In border systems, the runoff phase is estimated with less accuracy than the other phases. Therefore, use of the HD and ZI models is more suitable for estimating runoff in border method. Figure 2(e), shows satisfactory simulations of surface irrigation simulation models in basin irrigation. The VB model is not a reliable model to simulate basin irrigation systems. There are three important problems with a VB approach. First, the inflow during the advance phase must be steady. This is often difficult to achieve in the field. Second, if an intake equation with steady-state or cracking terms is used, the related parameters must be determined outside of the VB analysis and then input. These values are difficult to measure accurately in the field. And third, unless the analysis specifically ignores the surface volume during advance, these models use a uniform flow equation, like Manning, to describe the cross-sectional area of flow at the field inlet and then an assumption regarding the shape of the flow profile downstream – generally assuming the cross-sectional area is constant (Walker and Kasilingam, 2004). Therefore, applying the Saint-Venant equations is inevitable for simulation of basin irrigation. Figure 2(f) shows satisfactory simulations of irrigation phases in basin irrigation. In the most regions (according to the previous studies) basin irrigation carried out in level farms therefore, all of irrigation phases were estimated close together. As shown, the results of the models to predict the phases of each irrigation method (especially advance and infiltration events) were different. Because the assumptions applied in the various methods are effective in predicting the infiltration and advance times (Ebrahimian et al., 2010).

Figure 2 (a) Satisfactory simulations of surface irrigation simulation models in furrow irrigation (b) Satisfactory simulations of irrigation phases in furrow irrigation (c) Satisfactory simulations surface irrigation simulation models in border irrigation (d) Satisfactory simulations of irrigation phases in border irrigation (e) Satisfactory simulations of surface irrigation simulation models in basin irrigation (f) Satisfactory simulations of irrigation phases in basin irrigation (see online version for colours)

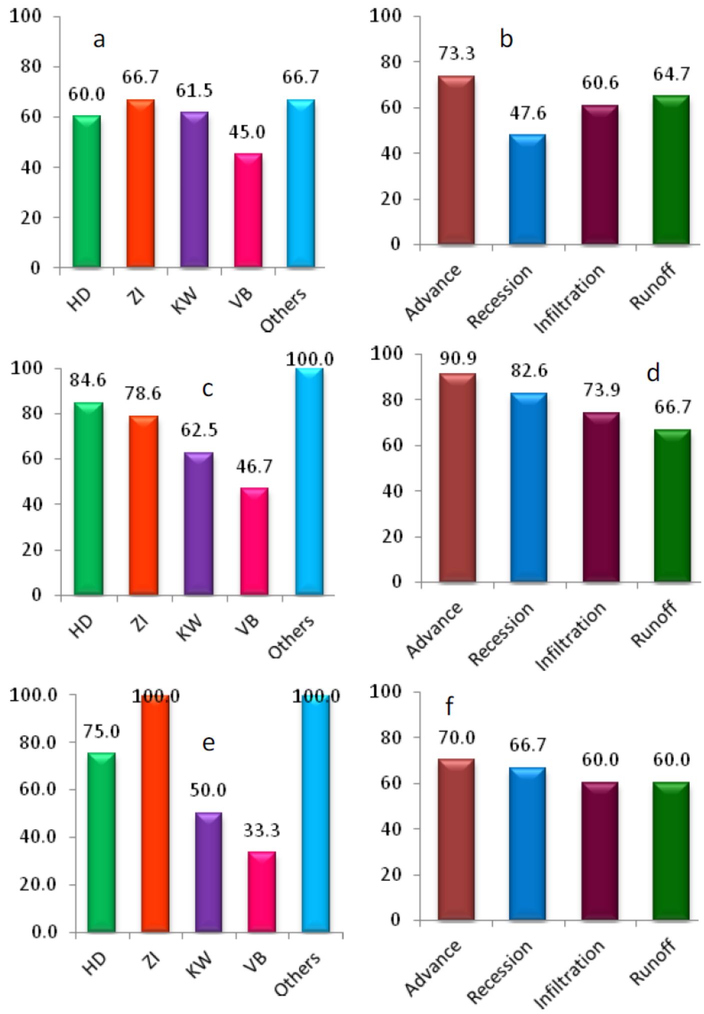
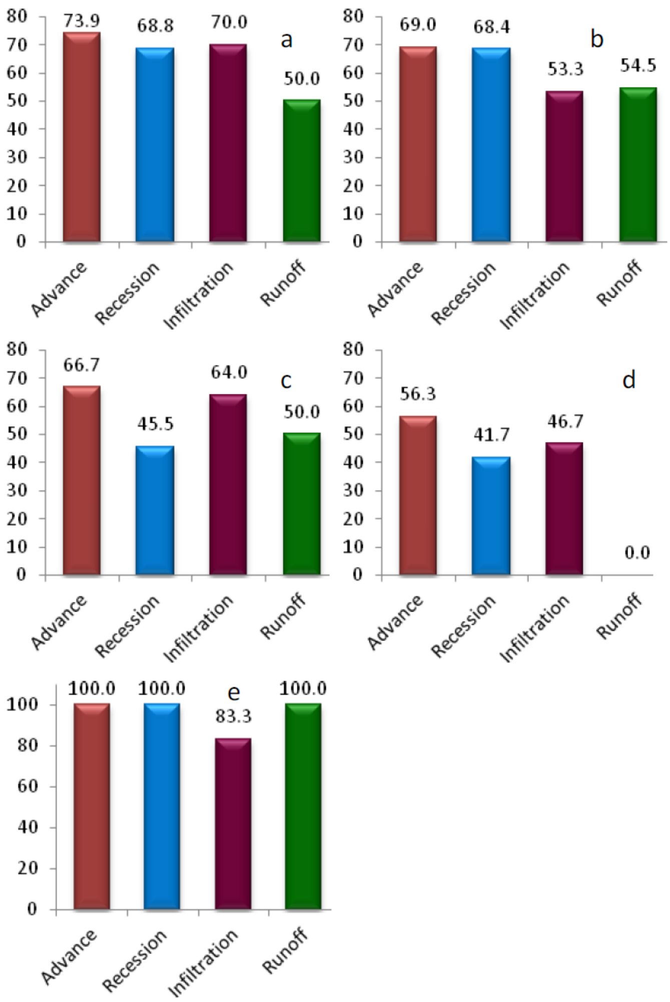


Figure 3 satisfactory simulations in the different models. As expected, precision of the HD model [Figure 3(a)] is better than the ZI, KW and VB models [Figures 3(b), 3(c) and 3(d)]. The ZI model is more suitable for prediction of advance and recession phases [Figure 3(b)] while the KW model is more suitable for prediction of advance and infiltration phases [Figure 3(c)] and the VB model could only predicted advance phase in more than half of its runs with a acceptable performance [Figure 3(d)]. There is no reported any successful application of the VB model for simulation of runoff phase. Therefore, the VB model is not recommended for predicting runoff phase due to the previous results [Figure 3(d)].

Figure 3 (a) Satisfactory simulations in HD model (b) Satisfactory simulations in ZI model (c) Satisfactory simulations in KW model (d) Satisfactory simulations in VB model (e) Satisfactory simulations in other models (see online version for colours)



To conclude the results, Table 1 was presented. According to Table 1, the priority of irrigation methods to simulate using the HD and other models is border, basin and furrow irrigation. It is border, furrow, and basin for the KW and VB models. Finally, this priority is basin, border and furrow for the ZI model. In addition, priority of estimation of irrigation phases also depends to the surface irrigation simulation models. It should be noted that, the priorities were obtained according to the various conditions of all studies (e.g., different types of the soils, field conditions, etc.).

Table 1 Priority of simulation of different methods and phases of surface irrigation based on obtained results from the previous studies

Model		*Priority for irrigation method*		*Priority for irrigation phase*
HD	1	Border	1	Advance
	2	Basin	2	Infiltration
	3	Furrow	3	Recession
			4	Runoff
ZI	1	Basin	1	Advance
	2	Border	2	Recession
	3	Furrow	3	Runoff
			4	Infiltration
KW	1	Border	1	Advance
	2	Furrow	2	Infiltration
	3	Basin	3	Runoff
			4	Recession
VB	1	Border	1	Advance
	2	Furrow	2	Infiltration
	3	Basin	3	Recession
			4	Runoff
Others	1	Border	1	Advance
	2	Basin	2	Recession
	3	Furrow	3	Runoff
			4	Infiltration

References

Abbasi, F., Shooshtari, M.M. and Feyen, J. (2003) 'Evaluation of various surface irrigation numerical simulation models', *J. Irrig. Drain. Eng.*, Vol. 129, No. 3, pp.208–213.

Alazba, A. (2002) 'Simple mathematical model for water advance determination', *Irrig. Sci.*, Vol. 21, No. 2, pp.75–81.

Austin, N.R. and Prendergast, J.B. (1997) 'Use of kinematic wave theory to model irrigation on cracking soil', *Irrig. Sci.*, Vol. 18, No. 1, pp.1–10.

Bakker, D.M., Plunkett, G. and Sherrard, J. (2006) 'Application efficiencies and furrow infiltration functions of irrigations in sugar cane in the Ord River Irrigation Area of North Western Australia and the scope for improvement', *Agr. Water Manage.*, Vol. 83, Nos 1–2, pp.162–172.

Banihabib, M.E., Valipour, M. and Behbahani, S.M.R. (2012) 'Comparison of autoregressive static and artificial dynamic neural network for the forecasting of monthly inflow of Dez Reservoir', *J. Environ. Sci. Technol.*, Vol. 13, No. 4, pp.1–14 [online] http://jest.srbiau.ac.ir/?_action=articleInfo&article=84 (accessed 5 February 2012).

Bautista, E. and Wallender, W.W. (1992) 'Hydrodynamic furrow irrigation model with specified space steps', *J. Irrig. Drain. Eng.*, Vol. 118, No. 3, pp.450–465.

Bautista, E. and Wallender, W.W. (1993) 'Identification of furrow intake parameters from advance times and rates', *J. Irrig. Drain. Eng.*, Vol. 119, No. 2, pp.295–311.

Bradford, S.F. and Katopodes, N.D. (2001) 'Finite volume model for nonlevel basin irrigation', *J. Irrig. Drain. Eng.*, Vol. 127, No. 4, pp.216–223.

Camacho, E., Perez-Lucena, C., Roldan-Canas, J. and Alcaide, M. (1997) 'IPE: model for management and control of furrow irrigation in real time', *J. Irrig. Drain. Eng.*, Vol. 123, No. 4, pp.264–269.

Chen, B., Ouyang, Z., Sun, Z., Wu, L. and Li, F. (2013) 'Evaluation on the potential of improving border irrigation performance through border dimensions optimization: a case study on the irrigation districts along the lower Yellow River', *Irrig. Sci.*, Vol. 31, No. 4, pp.715–728.

Chow, V.T. (1959) *Open Channel Hydraulics*, McGraw-Hill Book Co., Inc., New York.

Dholakia, M., Misra, R. and Zaman, M.S. (1998) 'Simulation of border irrigation system using explicit MacCormack finite difference method', *Agr. Water Manage.*, Vol. 36, No. 3, pp.181–200.

Dong, Q., Xu, D., Zhang, S., Bai, M. and Li, Y. (2013) 'A hybrid coupled model of surface and subsurface flow for surface irrigation', *J. Hydrol.*, Vol. 500, pp.62–74.

Douglas, P., Dassanayake, K.B., Chapman, D.F., Johnson, I.R., Khanna, M. and Malano, H. (2010) 'An integrated model for simulation of border-check irrigated dairy pasture production systems', *Comput. Electron. Agr.*, Vol. 74, No. 1, pp.39–50.

Ebrahimian, H. and Liaghat, A. (2011) 'Field evaluation of various mathematical models for furrow and border irrigation systems', *Soil Water Res.*, Vol. 6, No. 2, pp.91–101.

Ebrahimian, H., Liaghat, A., Ghanbarian-Alavijeh, B. and Abbasi, F. (2010) 'Evaluation of various quick methods for estimating furrow and border infiltration parameters', *Irrig. Sci.*, Vol. 28, No. 6, pp.479–488.

Eldeiry, A., Garcia, L.A., El-Zaher, A.S.A, and Kiwan, M.E. (2005) 'Furrow irrigation system design for clay soils in arid regions', *Appl. Eng. Agr.*, Vol. 21, No. 3, pp.411–420.

Esfandiari, M. and Maheshwari, B.L. (2001) 'SW – soil and water: field evaluation of furrow irrigation models', *J. Agr. Eng. Res.*, Vol. 79, No. 4, pp.459–479.

Feyen, J. and Zerihun, D. (1999) 'Assessment of the performance of border and furrow irrigation systems and the relationship between performance indicators and system variables', *Agr. Water Manage.*, Vol. 40, Nos. 2–3, pp.353–362.

Fonteh, M.F. and Podmore, T. (1993) 'A physically based infiltration model for furrow irrigation', *Agr. Water Manage.*, Vol. 23, No. 4, pp.271–284.

Fonteh, M.F. and Podmore, T. (1994) 'Application of geostatistics to characterize spatial variability of infiltration in furrow irrigation', *Agr. Water Manage.*, Vol. 25, No. 2, pp.153–165.

Gharbi, A., Daghari, H. and Cherif, K. (1993) 'Effect of flow fluctuations on free draining, sloping furrow and border irrigation systems', *Agr. Water Manage.*, Vol. 24, No. 4, pp.299–319.

Gillies, M.H., Smith, R.J. and Raine, S.R. (2007) 'Accounting for temporal inflow variation in the inverse solution for infiltration in surface irrigation', *Irrig. Sci.*, Vol. 25, No. 2, pp.87–97.

Gonzalez, C., Cervera, L. and Moret-Fernandez, D. (2011) 'Basin irrigation design with longitudinal slope', *Agr. Water Manage.*, Vol. 98, No. 10, pp.1516–1522.

Guardo, M. (1995) 'A volume balance solution for water flow over flat soil surfaces', *JAWRA J. Am. Water Resour. Assoc.* Vol. 31, No. 6, pp.1089–1099.

Guardo, M., Oad, R. and Podmore, T.H. (2000) 'Comparison of zero-inertia and volume balance advance-infiltration models', *J. Hydraul. Eng.*, Vol. 126, No. 6, pp.457–465.

Holzapfel, E.A., Leiva, C., Marino, M.A., Paredes, J., Arumi, J.L. and Billib, M. (2010) 'Furrow irrigation management and design criteria using efficiency parameters and simulation models', *Chile. J. Agr. Res.*, Vol. 70, No. 2, pp.287–296.

Holzapfel, E.A., Marino, M.A. and Chavez-Morales, J. (1984) 'Comparison and selection of furrow irrigation models', *Agr. Water Manage.*, Vol. 9, No. 2, pp.105–125.

Hori, T., Sugimoto, T., Nakayama, M., Ichikawa, Y. and Shiiba, M. (2008) 'Estimation of field irrigation water demand based on lumped kinematic wave model considering soil moisture balance', *Phys. Chem. Earth Part. A/B/C.*, Vol. 33, No. 5, pp.376–381.

Hume, I.H. (1993) 'Determination of infiltration characteristics by volume balance for border check irrigation', *Agr. Water Manage.*, Vol. 23, No. 1, pp.23–39.

Izuno, F.T. and Podmore, T.H. (1986) 'Surge irrigation management', *Agr. Water Manage.*, Vol. 11, No. 3, pp.279–291.

Jain, S.K. and Singh, V.P. (1989) 'A numerical kinematic wave model for border irrigation', *Irrig. Sci.*, Vol. 10, No. 4, pp.253–263.

Jaynes, D.B. (1986) 'Simple model of border irrigation', *J. Irrig. Drain. Eng.*, Vol. 112, No. 2, pp.172–184.

Kang, M.G., Park, S.W. and Park, J.M. (2009) 'Identifying two-dimensional characteristics of surface water hydraulics in an irrigated paddy field', *J. Irrig. Drain. Eng.*, Vol. 135, No. 4, pp.431–442.

Katopodes, N.D. (1994) 'Hydrodynamics of surface irrigation: vertical structure of the surge front', *Irrig. Sci.*, Vol. 15, Nos. 2–3, pp.101–111.

Katopodes, N.D., Tang, J.H. and Clemmens, A.J. (1990) 'Estimation of surface irrigation parameters', *J. Irrig. Drain. Eng.*, Vol. 116, No. 5, pp.676–696.

Khanna, M. and Malano, H.M. (2006) 'Modelling of basin irrigation systems: a review', *Agr. Water Manage.*, Vol. 83, No. 1, pp.87–99.

Khatri, K.L. and Smith, R.J. (2007) 'Toward a simple real-time control system for efficient management of furrow irrigation', *Irrig. Drain.*, Vol. 56, No. 4, pp.463–475.

Latif, M. and Mahmood, S. (2004) 'Field measurement and simulation of advance rates for continuous and surge irrigated furrows in Pakistan', *Irrig. Drain.*, Vol. 53, No. 4, pp.437–447.

Mahdizadeh Khasraghi, M., Gholami Sefidkouhi, M.A. and Valipour, M. (2014) 'Simulation of open- and closed-end border irrigation systems using SIRMOD', *Arch. Agron. Soil Sci.*, doi: 10.1080/03650340.2014.981163, in press.

Maheshwari, B.L. (1992) 'Effects of recession criteria on prediction of recession times in border irrigation models', *Agr. Water Manage.*, Vol. 21, No. 3, pp.167–176.

Maheshwari, B.L., McMahon, T.A. and Turner, A.K. (1990) 'Sensitivity analysis of parameters of border irrigation models', *Agr. Water Manage.*, Vol. 18, No. 4, pp.277–287.

Mailapalli, D.R., Singh, R. and Raghuwanshi, N.S. (2009) 'Physically based model for simulating flow in furrow irrigation. I: Model development', *J. Irrig. Drain. Eng.*, Vol. 135, No. 6, pp.739–746.

Mailhol, J.C. and Gonzalez, J.M. (1993) 'Furrow irrigation model for real-time applications on cracking soils', *J. Irrig. Drain. Eng.*, Vol. 119, No. 5, pp.768–783.

McClymont, D.J. and Smith, R.J. (1996) 'Infiltration parameters from optimisation on furrow irrigation advance data', *Irrig. Sci.*, Vol. 17, No. 1, pp.15–22.

Mohamed, H.I., Abass, O.M., Elabdin, Z. and Alla, A.R. (2010) 'Development of a Muskingum-Cunge routing model for design of furrow irrigation', *Agr. Biol. J. North. Am.*, Vol. 1, No. 5, pp.1014–1030.

Mohamoud, Y.M. (1992) 'Evaluating Manning's roughness coefficients for tilled soils', *J. Hydrol.*, Vol. 135, Nos. 1–4, pp.143–156.

Nasseri, A., Neyshabori, M.R. and Abbasi, F. (2008) 'Effectual components on furrow infiltration', *Irrig. Drain.*, Vol. 57, No. 4, pp.481–489.

Raghuwanshi, N.S. and Wallender, W.W. (1996) 'Modeling Seasonal Furrow Irrigation', *J. Irrig. Drain. Eng.*, Vol. 122, No. 4, pp.235–242.

Raghuwanshi, N.S., Saha, R., Mailapalli, D.R. and Upadhyaya, S.K. (2011) 'Infiltration evaluation strategy for border irrigation management', *J. Irrig. Drain. Eng.*, Vol. 137, No. 9, pp.602–609.

Raghuwanshi, N.S. and Wallender, W.W. (1998) 'Optimization of furrow irrigation schedules, designs and net return to water', *Agr. Water Manage.*, Vol. 35, No. 3, pp.209–226.

Rahimi, S., Gholami Sefidkouhi, M.A., Raeini-Sarjaz, M. and Valipour, M. (2015) 'Estimation of actual evapotranspiration by using MODIS images (a case study: Tajan catchment)', *Arch. Agron. Soil Sci.*, Vol. 61, No. 5, pp.695–709.

Ram, R.S. and Singh, V.P. (1982) 'Evaluation of models of border irrigation recession', *J. Agr. Eng. Res.*, Vol. 27, No. 3, pp.235–252.

Ram, R.S., Singh, V.P. and Prasad, S.N. (1986) 'A quasi-steady state integral model for closed-end border irrigation', *Agr. Water Manage.*, Vol. 11, No. 1, pp.39–57.

Ranjha, A.Y., Peralta, R.C., Requena, A.M., Deer, H.M., Ehteshami, M., Hill, R.W. and Walker, W.R. (1992) 'Best management of pesticide – furrow irrigation systems', *Irrig. Sci.*, Vol. 13, No. 1, pp.9–14.

Rayej, M. and Wallender, W.W. (1987) 'Furrow model with specified space intervals', *J. Irrig. Drain. Eng.*, Vol. 113, No. 4, pp.536–548.

Rayej, M. and Wallender, W.W. (1988) 'Time solution of kinematic-wave model with stochastic infiltration', *J. Irrig. Drain. Eng.*, Vol. 114, No. 4, pp.605–621.

Reddy, J.M. and Singh, V.P. (1994) 'Modeling and error analysis of kinematic-wave equations of furrow irrigation', *Irrig. Sci.*, Vol. 15, No. 2–3, pp.113–121.

Renault, D. and Wallender, W.W. (1996) 'Initial-inflow-variation impacts on furrow irrigation evaluation', *J. Irrig. Drain. Eng.*, Vol. 122, No. 1, pp.7–14.

Saha, R., Upadhyaya, S.K. and Wallender, W. (2009) 'Modified Horton's equation to model advance trajectory in furrow irrigation systems', *J. Irrig. Drain. Eng.*, Vol. 136, No. 4, pp.248–253.

Sakkas, J.G., Bellos, C.V. and Klonaraki, M.N. (1994) 'Numerical computation of surface irrigation', *Irrig. Sci.*, Vol. 15, Nos. 2–3, pp.83–99.

Schmitz, G.H. and Seus, G.J. (1990) 'Mathematical zero-inertia modeling of surface irrigation: advance in borders', *J. Irrig. Drain. Eng.*, Vol. 116, No. 5, pp.603–615.

Schmitz, G.H. and Seus, G.J. (1992) 'Mathematical zero-inertia modeling of surface irrigation: advance in furrows', *J. Irrig. Drain. Eng.*, Vol. 118, No. 1, pp.1–18.

Singh, V.P. (1980) 'Derivation of shape factors for border irrigation advance', *Agr. Water Manage.*, Vol. 2, No. 4, pp.271–288.

Singh, V.P. and He, Y.C. (1988) 'Muskingum model for furrow irrigation', *J. Irrig. Drain. Eng.*, Vol. 114, No. 1, pp.89–103.

Singh, V.P. and Ram, R.S. (1983) 'A kinematic model for surface irrigation: verification by experimental data', *Water Resour. Res.* Vol. 19, No. 6, pp.1599–1612.

Singh, V.P., Scarlatos, P.D. and Raudales, S.A. (1988) 'Muskingum model for border irrigation', *J. Irrig. Drain. Eng.*, Vol. 114, No. 2, pp.266–280.

Singh, V.P. and Yu, F.X. (1987) 'A mathematical model for border irrigation III. Evaluation of models', *Irrig. Sci.*, Vol. 8, No. 3, pp.191–213.

Singh, V.P. and Yu, F.X. (1989) 'An analytical closed border irrigation model I. Theory', *Agr. Water Manage.*, Vol. 15, No. 3, pp.223–241.

Soroush, F., Fenton, J.D., Mostafazadeh-Fard, B., Mousavi, S.F. and Abbasi, F. (2013) 'Simulation of furrow irrigation using the Slow-change/slow-flow equation', *Agr. Water Manage.*, Vol. 116, pp.160–174.

Strelkoff, T. (1969) 'One-dimensional equation of open channel flow', *J. Hydraul. Div.*, Vol. 95, No. 3, pp.861–876.

Strelkoff, T. and Katapodes, N.D. (1977) 'Border irrigation hydraulics with zero-inertia', *J. Irrig. Drain. Div.*, Vol. 103, No. 3, pp.325–342.

Tabuada, M.A., Rego, Z.J.C., Vachaud, G. and Pereira, L.S. (1995) 'Modelling of furrow irrigation. Advance with two-dimensional infiltration', *Agr. Water Manage.*, Vol. 28, No. 3, pp.201–221.

Turbak, A.S. and Morel-Seytoux, H.J. (1988a) 'Analytical solutions for surface irrigation. I: constant infiltration rate', *J. Irrig. Drain. Eng.*, Vol. 114, No. 1, pp.31–47.

Turbak, A.S. and Morel-Seytoux, H.J. (1988b) 'Analytical solutions for surface irrigation. II: variable infiltration rate', *J. Irrig. Drain. Eng.*, Vol. 114, No. 1, pp.48–60.

Upadhyaya, S.K. and Raghuwanshi, N.S. (1999) 'Semiempirical infiltration equation for furrow irrigation systems', *J. Irrig. Drain. Eng.*, Vol. 125, No. 4, pp.173–178.

Valiantzas, J.D. (2000) 'Surface water storage independent equation for predicting furrow irrigation advance', *Irrig. Sci.*, Vol. 19, No. 3, pp.115–123.

Valiantzas, J.D. (2001) 'Optimal furrow design. I: time of advance equation', *J. Irrig. Drain. Eng.*, Vol. 127, No. 4, pp.201–208.

Valiantzas, J.D., Aggelides, S. and Sassalou, A. (2001) 'Furrow infiltration estimation from time to a single advance point', *Agr. Water Manage.*, Vol. 52, No. 1, pp.17–32.

Valipour, M. (2012) 'Comparison of surface irrigation simulation models: full hydrodynamic, zero inertia, kinematic wave', *J. Agr. Sci.*, Vol. 4, No. 12, pp.68–74.

Valipour, M. (2013) 'Increasing irrigation efficiency by management strategies: cutback and surge irrigation', *ARPN J. Agr. Biol. Sci.*, Vol. 8, No. 1, pp.35–43.

Valipour, M. (2014a) 'A comprehensive study on irrigation management in Asia And Oceania', *Arch. Agron. Soil Sci.*, doi: 10.1080/03650340.2014.986471, in press.

Valipour, M. (2014b) 'Future of the area equipped for irrigation', *Arch. Agron. Soil Sci.*, Vol. 60, No. 12, pp.1641–1660.

Valipour, M. (2014c) 'Drainage, waterlogging, salinity', *Arch. Agron. Soil Sci.*, Vol. 60, No. 12, pp.1625–1640.

Valipour, M. (2014d), 'Future of agricultural water management in Africa', *Arch. Agron. Soil Sci.*, doi: 10.1080/03650340.2014.961433, in press.

Valipour, M. (2015) 'Log-term runoff study using SARIMA and ARIMA models in the United States', *Meteorol. Appl.*, doi: 10.1002/met.1491, in press.

Valipour, M. and Montazar, A.A. (2012a) 'An evaluation of SWDC and WinSRFR models to optimize of infiltration parameters in furrow irrigation', *Am. J. Sci. Res.*, Vol. 69, pp.128–142 [online] http://vali-pour.webs.com/4.pdf (accessed 25 August 2012).

Valipour, M. and Montazar, A.A. (2012b) 'Optimize of all effective infiltration parameters in furrow irrigation using Visual Basic and genetic algorithm programming', *Austral. J. Basic Appl. Sci.*, Vol. 6, No. 6, pp.132–137.

Valipour, M. and Montazar, A.A. (2012c) 'Sensitive analysis of optimized infiltration parameters in SWDC model', *Adv. Environ. Biol.*, Vol. 6, No. 9, pp.2574–2581.

Valipour, M., Ziatabar Ahmadi, M., Raeini-Sarjaz, M., Gholami Sefidkouhi, M.A., Shahnazari, A., Fazlola, R. and Darzi-Naftchali, A. (2015) 'Agricultural water management in the world during past half century', *Arch. Agron. Soil Sci.*, Vol. 61, No. 5, pp.657–678.

Walker, W. and Kasilingam, B. (2004) 'Correcting the volume balance equation for shape factors during advance', *Critical Transitions in Water and Environmental Resources Management*, 27 June–1 July, Salt Lake City, Utah, USA, pp.1–6.

Walker, W.R. (2005) 'Multilevel calibration of furrow infiltration and roughness', *J. Irrig. Drain. Eng.*, Vol. 131, No. 2, pp.129–136.

Walker, W.R. and Busman, J.D. (1990) 'Real-time estimation of furrow infiltration', *J. Irrig. Drain. Eng.*, Vol. 116, No. 3, pp.299–318.

Walker, W.R. and Humpherys, A.S. (1983) 'Kinematic-wave furrow irrigation model', *J. Irrig. Drain. Eng.*, Vol. 109, No. 4, pp.377–392.

Wallender, W.W. and Yokokura, J. (1991) 'Space solution of kinematic-wave model by time iteration', *J. Irrig. Drain. Eng.*, Vol. 117, No. 1, pp.140–144.

Weibo, N., Liangjun, F. and Xiaoyi, M. (2012) 'Estimated infiltration parameters and manning roughness in border irrigation', *Irrig. Drain.*, Vol. 61, No. 2, pp.231–239.

Wilson, B.N. and Elliott, R.L. (1988) 'Furrow advance using simple routing models', *J. Irrig. Drain. Eng.*, Vol. 114, No. 1, pp.104–117.

Wohling, T., Singh, R. and Schmitz, G.H. (2004) 'Physically based modeling of interacting surface-subsurface flow during furrow irrigation advance', *J. Irrig. Drain. Eng.*, Vol. 130, No. 5, pp.349–356.

Yitayew, M., Letey, J., Vaux Jr., H.J. and Feinerman, E. (1985) 'Factors affecting uniformity and optimal water management with furrow irrigation', *Irrig. Sci.*, Vol. 6, No. 3, pp.201–210.

Yu, F.X. and Singh, V.P. (1989) 'Analytical model for border irrigation', *J. Irrig. Drain. Eng.*, Vol. 115, No. 6, pp.982–999.

Zerihun, D., Feyen, J. and Reddy, J.M. (1996) 'Sensitivity analysis of furrow-irrigation performance parameters', *J. Irrig. Drain. Eng.*, Vol. 122, No. 1, pp.49–57.

Zhang, S., Xu, D., Bai, M. and Li, Y. (2014a) 'Two-dimensional surface water flow simulation of basin irrigation with anisotropic roughness', *Irrig. Sci.*, Vol. 32, No. 1, pp.41–52.

Zhang, S., Xu, D., Bai, M., Li, Y. and Xia, Q. (2014b) 'Two-dimensional zero-inertia model of surface water flow for basin irrigation based on the standard scalar parabolic type', *Irrig. Sci.*, Vol. 32, No. 4, pp.267–281.

Zhang, S., Xu, D. and Li, Y. (2011) 'A one-dimensional complete hydrodynamic model of border irrigation based on a hybrid numerical method', *Irrig. Sci.*, Vol. 29, No. 2, pp.93–102.