Indian Journal of Agricultural Sciences **84** (3): 337–42, March 2014/Article
https://doi.org/10.56093/ijas.v84i3.38563

Modeling soil water movement and irrigation management strategies in jujube (*Ziziphus jujuba*) orchard using HYDRUS-1D

SHUIXIAN WANG[1] and HAIYAN MA[2]

College of Earth and Environmental Sciences, Lanzhou University, Lanzhou, China 730000

Received: 3 March 2012; Revised accepted: 27 January 2014

ABSTRACT

In Xinjiang, an arid region located in the north-western China, water use for irrigation of predominantly jujube (*Ziziphus jujuba* Mill.) is high whereas water use efficiency is low. Due to that, how to increase irrigation efficiency is highly concerned by the local agricultural authorities. To quantify the irrigation water deep leakage and soil water balance, water application, crop growth, and soil water dynamics were studied on a sandy loam, sandy, and clay field in the years 2010 and 2011. Research shows that the soil water model HYDRUS-1D can be used as a tool to simulate and quantify improved management strategies and update irrigation standards in this region. The parameters sensitivity analysis result showed that soil water bottom flux was sensitive to θ_s and K_s in soil layers. The simulation results indicated that soil water leakage was influenced by soil texture, irrigation quota and irrigation frequency, and so on. In addition, soil water leakage was very serious under the traditional surface irrigation during jujube growth period. Soil water leakage mainly occurred in growth from mid-June to mid-August, which is the key period for jujube tree demand water, resulting in severe soil water leakage. Therefore, for improving the efficiency of irrigation water use and reducing the deep soil water leakage, it is not suitable to adopt surface irrigation in the study areas. Several different scenarios have been generated to better understand the effect of irrigation management on soil water leakage by HYDRUS-1D model in the study areas. The drip irrigation can reduce soil water leakage. Consequently, it should be recommend adopting drip irrigation technology, which would not only save water but also improve the efficiency of water use in the study areas.

Key words: HYDRUS 1D, Irrigation management, Infiltration, Jujube, Soil water movement

Water shortage has heightened the importance of water resource in agricultural production in arid regions(Patanè *et al*. 2011). Infiltration and evapotranspiration is the most important circle for agricultural water. Recently, many researchers concentrated on crop water requirements in arid regions (Neumann *et al.* 2011, Suárez *et al.* 2013, Yao *et al.* 2012). Other researchers concentrated on water infiltration using mathematical modelling (Jiang *et al*. 2010, Kandelous and Šimùnek 2010, Ma *et al*. 2010). Jujube (*Ziziphus jujuba* Mill.), a native fruit tree of China, is extensively cultivated in the Xinjiang Uygur Autonomous Region, China. The irrigation water requirement has been increased because of planted area expanded. Hence, water resources shortage has affected social and economic development in the whole region. At the same time, the traditional irrigation method has not only wasted a mass of water resource but also caused nitrogen loss with irrigation leaching, which may lead to ground water contamination (Loheide and Booth 2011, Shi *et al*. 2012). Recently, irrigated crop landscapes, however, increasingly experience water scarcity due to an intensification of agriculture and a growing water demand for household or municipal and industrial purposes (Lekakis *et al*. 2011, Li and Lascano 2011, Liu *et al*. 2012b, Panigrahi *et al*. 2012). Most water-soil models are developed by combining plant water use, soil water storage and water table fluctuations in varying degrees of complexity to predict current and future water-soil storage and plant water availability(Kandelous and Šimùnek 2010, Kukal and Hira 2009). The water and solute transport model Hydrus-1D (Šimùnek *et al*. 2003, Šimùnek *et al*. 2008) has been widely used in the last few years. HYDRUS-1D is a computer code based on the Richards equation for variably saturated water flow and the advection-dispersion equation for solute transport. The model has been successfully applied in numerous studies to analyse site-specific soil salinization, moisture, and plant growth problems (Abd Elrahman *et al*. 2012, Chen *et al*. 2010, Chhabra and Kumar 2008, Jiang *et al*. 2011, Siyal *et al*. 2012, Siyal *et al*. 2013, Xie *et al*. 2013).

This paper addresses the combined challenges of the arid irrigated areas of Xinjiang: water application, crop growth, and soil water dynamics. In this paper, HYDRUS-1D was used to simulate water movement during irrigation for jujube based on the field observations of soil water. Simulate and analyse improved management strategies and

[1] Associate Professor (e mail: wangshuixian@lzu.edu.cn), [2] Assistant Professor (e mail: mahy@lzu.edu.cn)

derive updated irrigation. In the end, this paper provides a reasonable suggestion for how to improve the efficiency of irrigation and save water.

MATERIALS AND METHODS

The field experiment was continuously conducted in 2010 at a farm located 22 km southeast of the city of Akesu city (Xinjiang, China) and it is enclosed between latitudes 39°30'N-41°27'N and longitudes 79°39'E-82°01'E. The site is in an extreme arid region with a mean annual temperature of 10°C, a mean annual precipitation of 52 mm, a mean annual evaporation from a free water surface of 2004 mm/ year and the index of dryness is 27.5, an average annual sunshine duration of 3900 h, and an annual accumulated temperature (higher than 10°C) of 3800°C. The groundwater table is consistently below 20 m. The soil is a sandy loam of loess origin. Soil layer is loam in 0 ~ 20cm, 20 ~ 70cm, soil layer is fine sand, 80 ~ 160cm soil layer is clay and below 160cm is rough sand in the study plot. Soil physical properties were shown in Table 1.

Soil volumetric content was measured by TRIME-IPH. Nine TRIME tube were installed in experimental sites. Soil moisture was measured once 1 day and the measurements would be intensified before and after rainfall or irrigation in difference soil depth (20, 40, 60, 80 cm). The Vantage pro2 automatic weather station was installed in study areas to calculate the potential evapotranspiration in jujube growth period. Automated data loggers collected micro-meteorological parameters including relative humidity, air temperature, wind speed, and radiation (net, solar, and photosynthetically-active) from 10 April to 10 October in 2010. Soil water leakage was measured by facility equipment. The TRAC was used to analyzer jujube tree leaf area index (LAI) for difference between potential evaporation and potential evapotranspiration. The leaf area index (LAI) was measured biweekly. Root lengths (cm) were measured in a randomly selected $1m^2$ in the study plot.

To determine soil hydraulic properties, representative soil horizons were sampled from the study plot. Soil samples in each plot were taken at 0–20, 20–70 and 70–150 cm. Soil hydraulic parameters for the soil were estimated using the Rosetta (Schaap *et al*. 2001) software. Rosetta is a software package that evaluates pedotransfer functions that use neural network models to predict soil hydraulic parameters from soil texture and related data for the van Genuchten-Mualem model (Van Genuchten 1980). The parameters required for the most complex model are the bulk density, percentages of sand, silt, and clay. For these input variables, Rosetta predicted the following soil hydraulic parameters of the van Genuchten-Mualem model, as shown in Table 2.

Table 1 Size classification for the experimental soils

Depth cm	Soil particles (%)			Density (g/cm^3)	Soil texture (g/cm^3)
	Sand 0.05–2.00 mm	Silt 0.002–0.05 mm	Clay < 0.002 mm		
0-20	63.2	27.0	9.8	1.5	Sandy loam
20-70	99.1	0.9	0.0	1.5	Fine sand
70-150	16.5	62.1	21.4	1.43	Clay

Table 2 Soil Hydraulic parameters

Soil depth (cm)	θ_r	θ_s	α	n	K_s	l
0-20	0.041	0.387	0.019	1.4029	39.1	0.5
20-70	0.05	0.3779	0.0351	2.68	712.8	0.5
70-150	0.0727	0.42	0.0052	1.6268	3	0.5

HYDRUS-1D is a Microsoft Windows based modeling environment for analysis of water flow and solute transport invariably saturated porous media. The program numerically solves the Richards' equation for saturated–unsaturated water flow and the Fickian-based advection–dispersion equation for solute transport (Šimùnek *et al*. 1998). The model requires the user to input soil and soil-water parameters, time stepping parameters, parameters defining the geometry, root water uptake patterns, solute transport parameters, and time variable boundary conditions (Šimùnek *et al*. 1998, Van Genuchten 1980). Detailed descriptions of the governing equations for water flow and solute transport and the invoked parameter optimization procedure are given by Abbasi *et al.* (Abbasi *et al*. 2003).

In the HYDRUS-1D model, observed soil water in the soil profile was taken as initial water content. For all simulated scenarios, the bottom boundary was defined by a unit vertical hydraulic gradient. Free drainage was selected as the boundary condition below 150 cm. The measured daily rainfall and potential evapotranspiration for the whole simulation period were used as a time-variable boundary for the plant-atmosphere interface, with irrigation incorporated into rainfall data.

The simulation period was started 184 days from 10 April in 2010 to 10 October in 2010 before the application to allow equilibrium of soil potentials and water contents over the winter period. However, only simulations for the post-application period are presented in this paper. Time discretization was as follows: initial time step 0.1 day, minimum time step 0.001 day, and maximum time step 5 day. The size of the model domain for study sites was 1.5 m in depth. The finite element grid consisted of a total of 151 nodes. Three layers were distinguished for the study site. Each layer was assumed to have uniform physical and chemical properties. The grid was spaced <10 cm in the unsaturated zone. For HYDRUS-1D model input, potential evapotranspiration (ET_p) was estimated by the Penman–Monteith equation according to the FAO-56 approach, using daily weather measurements, such as solar radiation, air temperature, humidity, and wind speed, as well as crop characteristics, such as minimum crop resistance, surface albedo, and crop height (Abdelhadi *et al*. 2000, Allen *et al.* 1998).

Table 3 Root uptake parameters of jujube tree in the model

P_0 (cm)	P_0pt (cm)	P_2H (cm)	P_2L (cm)	P_3 (cm)	r_2H (cm/d)	r_2L (cm/d)
-10	-25	-400	-400	-8000	0.5	0.1

In this study, the root water uptake is taken as a function of water in HYDRUS-1D model. Based on survey data, root lengths of the rhizome-grown jujube did not increase significantly during the simulating period. Therefore, the rooting depth was assumed to be fixed at 0.8m for this study. The root length density distribution was assumed to decline linearly with depth. The experimental data was best fit as shown in Table 3. These parameters were subsequently incorporated into the HYDRUS-1D model.

RESULTS AND DISCUSSION

Parameters sensitivity analysis

Sensitivity analysis is the study of how the uncertainty in the output of a mathematical model or system (numerical or otherwise) can be apportioned to different sources of uncertainty in its inputs (Abbasi *et al*. 2003, Rocha *et al*. 2006). In this study, the importance of soil hydraulic parameter uncertainty was estimated by performing a sensitivity analysis. For this analysis, the effect of ±25% parameter perturbations on the calculated cumulative actual soil water leakage was evaluated. Parameters considered for sensitivity analyses were θ_s, θ_r, a, n, K_s, and l. The simulation for *a* -25% perturbation of *n* was not completed because the small *n* value caused numerical difficulties in the simulation model. The sensitivity analysis result for the soil hydraulic parameters was showed in Table 4. Soil water bottom flux was least sensitive to θ_r, a, L and n in the soil layer. ±25% perturbation of these parameters in surface soil layers resulted in a change to the bottom flux. Bottom flux is less than 10%. Relatively high sensitivity in the soil layer was found for θ_s and K_s. ±25% perturbation of θ_s and K_s altered Bottom flux that ranged from 60% to 80% in the soil layer. Soil water bottom flux was sensitive to θ_s and K_s in soil layers. However, as it is impossible to confirm the sources of uncertainty with sensitivity analysis, future work aimed at quantifying uncertainty in all parameters above would greatly benefit efforts to determine uncertainty in bottom flow.

Model calibration and verification

Soil water content, *θ*, was measured from the soil profiles in the observation plots. The calibration period was from 10 April to 8 August 2010, and the verification period was from 9 August to 10 October 2010. The root mean square error (RMSE) was used to compare the modelling performances (Ma *et al*. 2010).

The simulation results for soil water content (Fig 1) showed the same tendencies as the measured values. The RMSE of soil water content during the calibration and validation periods is shown in Table 5. During the calibration period, the RMSE of different depth soil water content ranged from 0.0113 to 0.0153 cm^3/cm^3. During the validation period, the RMSE of different depth soil water content ranged from 0.0106 to 0.0206 cm^3/cm^3. The model correctly predicted the observed soil water content, showed the same tendencies as the measured values. The differences between the observed and simulated were partly due to spatial heterogeneity and observation errors, which are inevitable under field conditions (Shouse *et al*. 2011, Vazifedoust *et al*. 2008). The model results show the dynamic changes of soil water content and the simulation results of HYDRUS-1D are very close to the observed results, and it is feasible to simulate soil deep leakage using the model. The hydraulic parameters of calibration model as shown in Table 6.

Soil water balance and leakage analysis

In Table 7, the results showed soil water balance for the study areas. The root zone storage, root water uptake and soil leakage were computed from the simulation. The results showed that soil leakage was very high percentage (58.9%) occurred in study plot. The water consumption of jujube is

Table 4 Soil Hydraulic parameters sensitivity assessment

Sensitivity assessment criterion	Parameters	Parameters range (%) 0	Bottom flux (cm) 136.2	Bottom flux range (%) 0
	θr	–25	127.48	–6.399
		+25	144.92	+6.399
√	θs	–25	218.74	+60.60
√		+25	53.32	–60.85
	α	–25	139.78	+2.63
		+25	134.14	–1.51
	n	–25	138.30	+1.54
		+25	134.32	–1.38
√	Ks	–25	27.85	–79.55
√		+25	244.37	+79.42
	L	–25	136.20	0
		+25	136.20	0

Table 5 The RMSE of soil water content for the calibration and validation periods

	0-20		20-40		40-60		60-80	
	M	RMSE	M	RMSE	M	RMSE	M	RMSE
Calibration	121	0.0113	121	0.0135	121	0.0153	121	0.0116
Validation	63	0.0106	63	0.0206	63	0.0159	63	0.0125

Table 6 Soil Hydraulic parameters of calibrations model

Soil depth (cm)	θ_r	θ_s	α	n	K_s	l
0~20	0.041	0.387	0.019	1.403	39.1	0.5
20~70	0.050	0.378	0.035	2.680	712.8	0.5
70~150	0.073	0.470	0.005	1.627	3.0	0.5

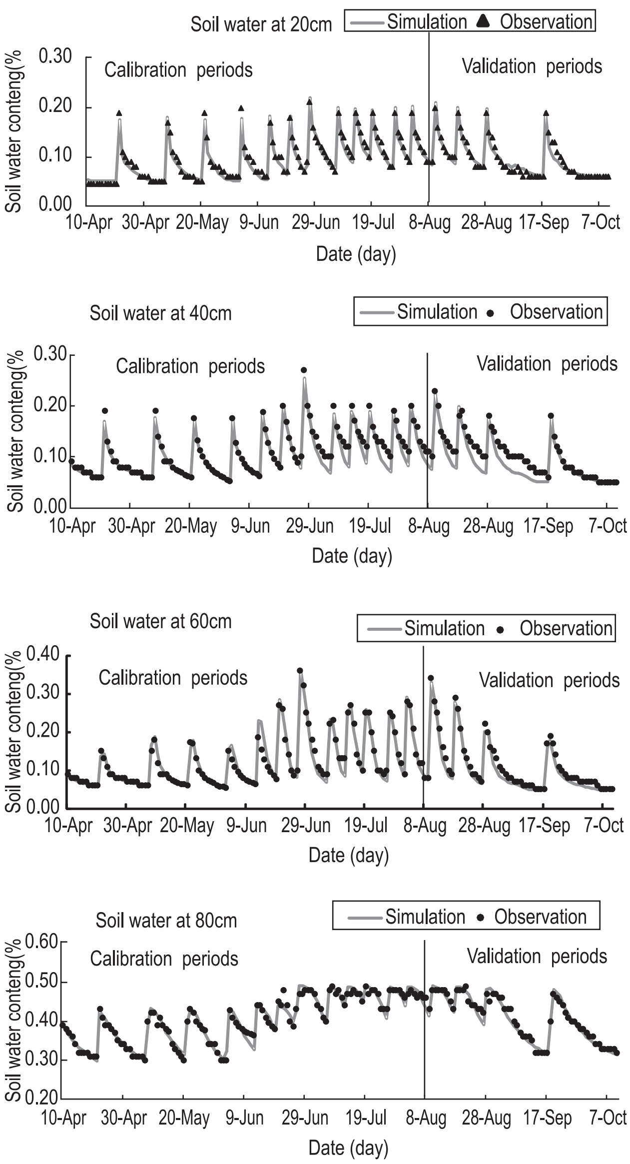

Fig 1 Measured and fitted soil water content at different soil depths in plots during the verification period

Table 7 Soil water balance during the growth stage of jujube

Item	Irriga-tion	Precipi-tation	Evapo-ration	Transpi-ration	Storage	Leakage
Amount (mm)	1872.5	35.8	389.2	413.4	-18.3	1124.0
% (irrigation +precipitation)	98.1	1.9	20.4	21.7	-1.0	58.9

42.1% under the surface water flux, and the transpiration is only 21.7%, which shown the efficiency of irrigation water use is very low. Soil water leakage was influenced by soil texture, irrigation and transpiration evaporation, and so on(Yao *et al*. 2012). Irrigation played a key role to affect irrigation water leakage. Excessive irrigation is most directly reason for soil water deeply leakage. Soil hydraulic properties played a greater role in controlling the soil leakage, and 0 ~ 70cm of soil is sand in the study plot. While irrigation water quota is too large and irrigation frequency is too high, the soil water seepage will be generated with the irrigation, so the irrigation and irrigation intensity will reduce in the study areas (Baudena *et al*. 2012, Verma *et al*. 2011).

The results showed the soil water leakage cumulative curve during the jujube growth. Soil water leakage was very serious under the traditional surface irrigation during jujube growth period. The amount of cumulative leakage to 1124 mm about 60% of irrigation water, and soil water leakage mainly occurred in growth from mid-June to mid-August, which is the key period for jujube tree demand water, resulting in severe soil water leakage. So irrigation quota should increase to save water under a high irrigation frequency (Mastrocicco *et al*. 2010, Sun *et al*. 2011). Therefore, for improving the efficiency of irrigation water use and reducing the deep soil water leakage, it is not suitable to adopt flooding irrigation based on soil texture conditions of the study area. It should be recommended to adopt furrow irrigation or micro-irrigation technology using high frequency and little-ration irrigation methods in the study areas, which not only saves water but also improves the efficiency of water use.

Irrigation management strategies analysis

Optimal irrigation water management is supposed to address at least three aspects: maintaining favourable soil water content, preventing salinity stress, and saving as much water as possible (Forkutsa *et al.* 2009). In the study, according to the water requirement features of jujube different growth period water features; two improved-irrigation managements were developed to improve the traditional irrigation mode for farmers in the study area. The effects of irrigation methods on soil water leakage were analysed by HYDRUS-1D model. The results are shown in Table 8. Improved 1 and 2 can save water 112.5, 272.5 mm, respectively, compared with the traditional mode, by reducing irrigation quota in the whole growth period. Soil water leakage reduced by 222.5, 367.4 mm, respectively. For jujube water consumption, water consumption for irrigation water increased by 4.0% and 7.8%. As can be seen, improved 1 and 2 can save irrigation water, reduce the soil water leakage, and increase the effective utilization of irrigation water. But in the study, the test soil is sand, irrigation water infiltration is fast, irrigation cannot be completed if irrigation quota was excessively reduced.

Table 8 Effects of improved surface irrigation method on irrigation water deep leakage

Irrigation	Irrigated water frequency	Irrigated water quota (mm)	Irrigation quota (mm)	Leakage (mm)	Evapo-transpi-ration (mm)
Traditiona l	16	100~160	1872.5	1124.0	802.6
Improved 1	16	110	1760.0	901.5	825.5
Improved 2	16	100	1600.0	756.6	810.3

Table 9 Simulated soil water deep leakage and evapotranspiration under the micro-irrigation method

Scenarios	Irrigated water quota (mm)	Irrigation period (d)	Irrigated water frequency	Irrigation quota (mm)	Leakage (mm)	Evapotranspiration (mm)
1	20	4	37	740	30.1	687.6
2	25	4	37	925	86.1	801.9
3	30	4	37	1100	195.1	878.9
4	20	5	31	620	29.6	581.6
5	25	5	31	775	31.9	713.5
6	30	5	31	930	89.7	798.1

Therefore, surface irrigation is not suitable for the study area.

Drip irrigation is a kind of plant root zone for irrigation of local irrigation methods, with good water yield (Jinxia *et al.* 2012, Liu *et al.* 2012a, Panigrahi *et al.* 2012). Several different scenarios have been generated to better understand the effect of drip irrigation management on soil water leakage by HYDRUS-1D model in the arid areas. The results are shown in Table 9. As can be seen, scenario 1, 2, and 3, the irrigation quota decreased and the irrigation frequency increased will save water 1132.5, 947.5, 762.5 mm under drip-irrigation technology. The leakage rate decreased by 54%, 51%, 41%, and the jujube tree transpiration accounted for 92.9%, 86.7%, and 79.9% of irrigation water, respectively. Scenario 4, 5, and 6, the quota irrigation decreased and the frequency increased will save water 1252.5, 1097.5, and 942.5 mm. The leakage rate decreased by 55%, 56%, 50%, and the jujube tree transpiration accounted for 93.8%, 92.1%, and 85.8% of irrigation water, respectively. It indicates that drip irrigation conditions, the high frequency and small scale irrigation, water saving irrigation system will be effective in reducing the leakage of soil water, improving irrigation water use efficiency (Du *et al.* 2008, Gonçalves *et al.* 2007).

CONCLUSIONS

In this paper, soil water model was constructed using HYDRUS-1D model to improve our understanding the relation of irrigation and soil water leakage. This study compared HYDRUS-1D simulations of soil water with field observation data collected from the study site in the jujube orchard. Acceptable agreement between the model simulations and the observed data was achieved. This implies that the HYDRUS-1D model can be a useful tool for irrigation water management in this region. The study shows that irrigation water leakage is very large under traditional surface irrigation conditions, the quantity of soil water leakage is 1124.0mm during the growing period of jujube in 2010, and the rate of soil water deep leakage to irrigation water is 60%. So excessive irrigation is most reason for soil water changes and deep leakage in the Akesu region, and the intensity and frequency is the most direct factor for soil water deep leakage in the jujube orchard.

Several scenarios have been generated to better understand the effect of irrigation management on the soil water leakage in the arid areas. The results indicated that soil water leakage will decrease under drip irrigation conditions, and the high frequency and small scale irrigation will reduce the leakage of soil water, and improve irrigation water use efficiency. Therefore, for improving the efficiency of irrigation water use and reducing the deep soil water leakage, it is not suitable to adopt flooding irrigation based on soil texture conditions of the study area. It should be recommended to adopt micro-irrigation technology using high frequency and little-ration irrigation methods in the study areas, which not only saves water but also improves the efficiency of water use.

ACKNOWLEDGEMENTS

This work was supported by the National science and technology Research Program of China (NO. 2007BAD38B09), the Science and Technology Innovation program of MWR (Ministry of water resources), China (NO. 200801050) and the National Basic Research Program of China (No. 2007CB416604).

REFERENCES

Abbasi F, Simunek J, Feyen J, Van Genuchten M T and Shouse P. 2003. Simultaneous inverse estimation of soil hydraulic and solute transport parameters from transient field experiments: Homogeneous soil. *Transactions of the ASAE* **46** (4): 1 085–95.

Abd Elrahman S H, Mostafa M A M, Taha T A, Elsharawy M A O and Eid M A. 2012. Effect of different amendments on soil chemical characteristics, grain yield and elemental content of wheat plants grown on salt-affected soil irrigated with low quality water. *Annals of Agricultural Sciences* **57** (2): 175–82.

Amer A M. 2011. Effects of water infiltration and storage in cultivated soil on surface irrigation. *Agricultural Water Management* **98** (5): 815–22.

Baudena M, Bevilacqua I, Canone D, Ferraris S, Previati M and Provenzale A. 2012. Soil water dynamics at a midlatitude test site: Field measurements and box modeling approaches. *Journal of Hydrology* **414–415** (0): 329–40.

Chen W, Hou Z, Wu L, Liang Y and Wei C. 2010. Evaluating salinity distribution in soil irrigated with saline water in arid regions of northwest China. *Agricultural Water Management* **97** (12): 2 001–8.

Chhabra R and Kumar A. 2008. Effect of water-table depths and groundwater salinities on the growth and biomass production of different forest species. *Indian Journal of Agricultural Sciences* **78** (9): 785–90.

Du T, Kang S, Zhang J, Li F and Yan B. 2008. Water use efficiency and fruit quality of table grape under alternate partial root-zone drip irrigation. *Agricultural Water Management* **95** (6): 659–68.

Forkutsa I, Sommer R, Shirokova Y I, Lamers J P A, Kienzler K, Tischbein B, Martius C and Vlek P L G. 2009. Modeling irrigated cotton with shallow groundwater in the Aral Sea Basin of Uzbekistan: I. Water dynamics. *Irrigation Science* **27** (4): 331–46.

Gonçalves J M, Pereira L S, Fang S X and Dong B. 2007. Modelling and multicriteria analysis of water saving scenarios for an irrigation district in the upper Yellow River Basin. *Agricultural Water Management* **94** (1-3): 93–108.

Jiang J, Feng S, Huo Z, Zhao Z and Jia B. 2011. Application of the SWAP model to simulate water–salt transport under deficit irrigation with saline water. *Mathematical and Computer Modelling* **54** (3-4): 902–11.

Jiang S, Pang L, Buchan G D, Šimùnek J, Noonan M J and Close M E. 2010. Modeling water flow and bacterial transport in undisturbed lysimeters under irrigations of dairy shed effluent and water using HYDRUS-1D. *Water Research* **44** (4): 1050–61.

Jinxia Z, Ziyong C and Rui Z. 2012. Regulated deficit drip irrigation influences on seed maize growth and yield under film. *Procedia Engineering* **28** (0): 464–8.

Kandelous M M and Šimùnek J. 2010. Numerical simulations of water movement in a subsurface drip irrigation system under field and laboratory conditions using HYDRUS-2D. *Agricultural Water Management* **97** (7): 1070–6.

Kukal S and Hira G. 2009. Root growth and soil water dynamics in relation to organic and inorganic fertilization in rice (*Oryza sativa*)-wheat (*Triticum aestivum*) cropping system. *Indian Journal of Agricultural Sciences* **79** (11): 922–6.

Lekakis E H, Georgiou P E, Pavlatou-Ve A and Antonopoulos V Z. 2011. Effects of fixed partial root-zone drying irrigation and soil texture on water and solute dynamics in calcareous soils and corn yield. *Agricultural Water Management* **101** (1): 71–80.

Li H and Lascano R J. 2011. Deficit irrigation for enhancing sustainable water use: Comparison of cotton nitrogen uptake and prediction of lint yield in a multivariate autoregressive state-space model. *Environmental and Experimental Botany* **71** (2): 224–31.

Liu H, Yang H, Zheng J, Jia D, Wang J, Li Y and Huang G. 2012a. Irrigation scheduling strategies based on soil matric potential on yield and fruit quality of mulched-drip irrigated chili pepper in Northwest China. *Agricultural Water Management* **115** (0): 232–41.

Liu M-x, Yang J-s, Li X-m, Yu M and Wang J. 2012b. Effects of irrigation water quality and drip tape arrangement on soil salinity, soil moisture distribution, and cotton yield (*Gossypium hirsutum* L.) under mulched drip irrigation in Xinjiang, China. *Journal of Integrative Agriculture* **11**(3): 502–11.

Loheide S P and Booth E G. 2011. Effects of changing channel morphology on vegetation, groundwater, and soil moisture regimes in groundwater-dependent ecosystems. *Geomorphology* **126** (3–4): 364–76.

Ma Y, Feng S, Su D, Gao G and Huo Z. 2010. Modeling water infiltration in a large layered soil column with a modified Green–Ampt model and HYDRUS-1D. *Computers and Electronics in Agriculture,* 71, Supplement **1** (0): S40–S47.

Mastrocicco M, Colombani N, Salemi E and Castaldelli G. 2010. Numerical assessment of effective evapotranspiration from maize plots to estimate groundwater recharge in lowlands. *Agricultural Water Management* **97** (9): 1389–98.

Neumann L E, Šimùnek J and Cook F J. 2011. Implementation of quadratic upstream interpolation schemes for solute transport into HYDRUS-1D. *Environmental Modelling & Software* **26** (11): 1 298–308.

Panigrahi P, Srivastava A K and Huchche A D. 2012. Effects of drip irrigation regimes and basin irrigation on Nagpur mandarin agronomical and physiological performance. *Agricultural Water Management* **104** (0): 79–88.

Patanè C, Tringali S and Sortino O. 2011. Effects of deficit irrigation on biomass, yield, water productivity and fruit quality of processing tomato under semi-arid Mediterranean climate conditions. *Scientia Horticulturae* **129** (4): 590–6.

Rocha D, Abbasi F and Feyen J. 2006. Sensitivity analysis of soil hydraulic properties on subsurface water flow in furrows. *Journal of Irrigation and Drainage Engineering* **132** (4): 418–24.

Schaap M G, Leij F J and van Genuchten M T. 2001. ROSETTA: a computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. *Journal of hydrology* **251** (3): 163–76.

Shi X, Fang R, Wu J, Xu H, Sun Y and Yu J. 2012. Sustainable development and utilization of groundwater resources considering land subsidence in Suzhou, China. *Engineering Geology* **124** (0): 77–89.

Shouse P J, Ayars J E and Šimùnek J. 2011. Simulating root water uptake from a shallow saline groundwater resource. *Agricultural Water Management* **98** (5): 784–90.

Šimùnek J, van Genuchten M T and Šejna M. 2008. Development and applications of the HYDRUS and STANMOD software packages and related codes. *Vadose Zone Journal* **7** (2): 587–600.

Siyal A A, Bristow K L and Šimùnek J. 2012. Minimizing nitrogen leaching from furrow irrigation through novel fertilizer placement and soil surface management strategies. *Agricultural Water Management* **115** (0): 242–51.

Siyal A A, van Genuchten M T and Skaggs T H. 2013. Solute transport in a loamy soil under subsurface porous clay pipe irrigation. *Agricultural Water Management* **121** (0): 73–80.

Suárez F, Guzmán E, Muñoz J F, Bachmann J, Ortiz C, Alister C and Kogan M. 2013. Simazine transport in undisturbed soils from a vineyard at the Casablanca valley, Chile. *Journal of Environmental Management* **117** (0): 32–41.

Sun Q, Kröbel R, Müller T, Römheld V, Cui Z, Zhang F and Chen X. 2011. Optimization of yield and water-use of different cropping systems for sustainable groundwater use in North China Plain. *Agricultural Water Management* **98** (5): 808–14.

Van Genuchten M T. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal* **44** (5): 892–8.

Vazifedoust M, Van Dam J, Feddes R and Feizi M. 2008. Increasing water productivity of irrigated crops under limited water supply at field scale. *Agricultural Water Management* **95** (2): 89–102.

Verma P, Yeates J and Daly E. 2011. A stochastic model describing the impact of daily rainfall depth distribution on the soil water balance. *Advances in Water Resources* **34** (8): 1 039–48.

Xie X, Wang Y, Ellis A, Su C, Li J, Li M and Duan M. 2013. Delineation of groundwater flow paths using hydrochemical and strontium isotope composition: A case study in high arsenic aquifer systems of the Datong basin, northern China. *Journal of Hydrology* **476** (0): 87–96.

Yao L, Feng S, Mao X, Huo Z, Kang S and Barry D A. 2012. Coupled effects of canal lining and multi-layered soil structure on canal seepage and soil water dynamics. *Journal of Hydrology* **430–431** (0): 91–102.

Zhou H H, Chen Y N and Li W H. 2010. Soil properties and their spatial pattern in an oasis on the lower reaches of the Tarim River, northwest China. *Agricultural Water Management* **97** (11): 1 915–22.