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Capillary Rise Simulation Using UPFLOW Model in Sugarcane Agro-industries of Khuzestan

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ABSTRACT

The upward movement of water through capillary rise from the shallow water-table (1–1.5 m) to the root zone (0.4–0.6 m) is an important incoming flux in the soil system. UPFLOW is a specialized model for determining capillary rise, which is a simple model with a small amount of input data. This research was conducted to assess the efficiency of the UPFLOW model in the simulation of capillary rise in shallow water-table conditions, based on the observed capillary rise using a lysimeter in the agro-industry of Amirkabir, Khuzestan. The input data of the model include: crop(root-water uptake rate at different sections of root zone, crop cover type, crop coefficient), soil(number of soil layers and their thickness, mean soil-water content of the profile, anaerobiosis point of the soil, saturated hydraulic conductivity of the soil profile), weather(maximum and minimum temperature, solar radiation, wind speed, and relative humidity, ET_0) and water-table(depth to water-table from the soil surface, salt content of the groundwater) were measured. Then, the capillary rise was calculated for each month during the stages of sugarcane growth. The performance of this model was evaluated by the statistical indices including determination coefficient (R^2), mean absolute error (MAE), root mean square error (RMSE), relative error (RE), and model efficiency (EF). The results of the field measurement showed that the highest amount of capillary rise (1.6 mm) was observed in July, with the maximum evapotranspiration (400 mm) and the maximum growth of sugarcane. The lowest value (0 mm) also was observed in the months when sugarcane growth stopped, i.e., November, December, January, and February. The results of this research have shown that the UPFLOW model in the studied area has not shown suitable efficiency (based on statistical indicators) in the simulation of the upward flow in specific conditions of water-table, crop, soil, climate, and management measures (R^2:0.23, MAE:8.71, RMSE:9.10, RE:180.50, EF: -136.40). Therefore, this model, in shallow water-table conditions, to accurately estimate capillary rise, requires comprehensive evaluations of various effective factors and, if possible, to modify and adjust this model in this area.

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1. Introduction

One of the major problems of agriculture in the south of Khuzestan, especially agro-industries, despite the existence of a regular drainage system, is the rise of salts from the groundwater to the root zone. The upward movement of solutes in the soil occurs due to the phenomenon of capillary rise, which can threaten agricultural lands and lead to a decrease in productivity and destruction of soil resources (Shini Dashtgol and Hamoudi, 2015; Saeedavi *et al.*, 2017). Factors affecting capillary rise include soil physical properties such as porosity and soil texture, as well as environmental conditions including evapotranspiration, plants, and water-table. Capillary rise is defined as the upward flow of water from the water-table to the root zone due to the potential difference between the soil surface and the underlying saturated layer (Caecelia *et al.*, 2004). Determining upward flow and capillary rise is a difficult matter and requires full knowledge of all factors affecting water flow in the soil, such as physical and chemical properties of the soil, and climatic and management factors (Lacour *et al.*, 2013).

It is difficult to measure the upward flow experimentally and directly in the fields, which requires a lot of time and cost. Unfortunately, direct measurement of the upward water movement in fields faces limitations in terms of high cost and implementation problems (Qureshi and Madramootoo, 2013). The lysimetric method is an acceptable approach to measure the capillary rise in the soil, in which the inputs and outputs of water in the soil can be controlled. Therefore, in this method, by creating a controlled environment in terms of crop cultivation and the input and output of water to the soil, the capillary rise is calculated to the acceptable form under natural conditions (Siddique *et al*., 2009). Laboratory methods are the basis for the development of simulating models, which over time have been converted into computer programs. Advanced water flow simulation models in unsaturated porous media can be reliably used to estimate upward flow and capillary rise in any type of environment, but it requires a wide range of data.

Various models have been developed in the world to measure capillary rise, and the basis of all these models are physical laws in water-soil relations. These models include Drinmod model, TSMA and QSSAM analytical models, NM numerical model, and Hydrus 3D model. These models are complex due to the need for diverse and a wide range of input data (Ali *et al.*, 2013). Raes (2003), developed a UPFLOW model to estimate upward water flux from a shallow water-table to the root zone during a specific period in a specific environment. The UPFLOW model may be used as useful software to predict the amount of capillary rise and upward flow, as well as to determine the moisture conditions in the soil. The UPFLOW is a fast, user-friendly tool, and highly customizable. It can be applied to situations with limited data availability and help researchers make estimates faster, and with more precision. Raes and Deproost (2002) evaluated the effects of capillary rise in Senegalese rice fields and Brazilian mango fields, and the measurements confirm that this model provides a correct simulation of the amount of water and salt flow to the root zone. They also evaluated this model in sandy loam and loamy sand soil in Belgium and concluded that the simulation of the capillary rise rate from the root zone is accurate. In Iran, limited research has been done on the capillary rise in soil, and due to the great effect of capillary rise on crop yield, especially in sugarcane fields, more research is needed on this phenomenon. Since limited research has been done on the capillary rise in Iran and the UPFLOW model has not been evaluated, the purpose of this study is to evaluate the capillary rise in the soils of southern Khuzestan and evaluate this model in agro-industries of Khuzestan.

2. Material and methods

2.1. The geographical location of the study area

This research was conducted at the Sugarcane Research Institute of Amirkabir agro-industry

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(2018), one of the ten units of the Sugarcane Development Company of Khuzestan. Amirkabir agro-industry is located 45 kilometers south of Ahvaz, west of the Karun River and east of the Ahvaz-Khorramshahr road, at longitude 12° 48´ to 30° 48´ and latitude 15° 31´ to 40° 31´. The mentioned region has a hot and dry climate with an average annual rainfall of 170 mm and an average annual temperature of 24 ºC.

The monthly mean air temperature ranges from a high of 51.5 °C observed in August to a low of -3.4 °C noted in February. The driest month is August, with 0 mm of rain. The average rainfall is 166.5 mm, most of which occurs in December. The average annual evaporation is 3693 mm and the average monthly wind speed (at a height of two meters) is 2.9 m/s, which is the highest evaporation and wind speed in July (Shini Dashtgol and Hamoudi, 2015). The characteristics of the included EC, SAR, Total Dissolved Solids (TDS), Total Hardness(TH), Anions, Biological oxygen demand(BOD), Chemical oxygen demand (COD) irrigation water are listed in Table 1.

Table 1. Irrigation water quality in the Amirkabir agro-industry

Property	EC(µS/cm)	SAR	TH(mg/l)	TDS(mg/l)	$SO4^{-2}$(meq/l)	Cl-(meq/l)	HCO^{-3} (meq/l)	$CO3^{-2}$(meq/l)	COD(mg/l)	BOD(mg/l)	Water Classification
Mean	1172.66	5.14	369.29	1397.86	4.09	9.64	3.18	0.00	20.93	8.00	
Min	1.52	4.20	199.00	600.00	1.00	6.00	3.00	0.00	18.00	4.00	C3S1
Max	2170.00	7.50	521.00	5000.00	7.00	15.50	3.50	0.00	26.00	12.00	C3S2
STDEV	614.67	1.04	73.53	1103.17	1.50	2.33	0.17	0.00	2.34	2.58	

TDS: Total Dissolved Solids; TH: Total Hardness; COD: Chemical oxygen demand; BOD: Biological oxygen demand

2.2. Capillary rise measurement

In this study, a volumetric lysimeter system with a drain, which is located in the Amir Kabir agro-industry, 45 km south of Ahvaz, was used (Figure 1). The basis of the drainage lysimeter is based on the principle that the amount of evapotranspiration is equal to the difference between the sum of irrigation water and rainfall and drainage water. Also, in this type of lysimeter, the water-table can be kept constant and the inputs and outputs of the system can be controlled. Some of the physicochemical properties of the lysimeters' soil are presented in Table 2.

Table 2. Some physical and chemical characteristics of soil in the Amirkabir agro-industry lysimeter

Soil Classification	Soil texture	I(mm/h)	FC(%vol)	PWP(%vol)	SP(%)	EC_s(dS/m)	EC_s(dS/m)	SAR	K_s(m/day)	Slope(%)	EC_w(dS/m)	WT(m)
Haplic Calcisols (Clayic)	Clay loam	1.4-3.4	37.8	17.2	48	1.3-5.5	1.3-5.5	1-3	0-2.7	0.005	2.4	0.75-1.2

I: Infiltration; FC: Field capacity; PWP: Permanent wilting point; SP: Saturation point; EC_s:Soil electrical conductivity; K_s:Saturated hydraulic conductivity; EC_w: Water electrical conductivity; WT:Water-table

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The soil was a deep clay loam with an organic carbon content of 0.70 percent. In this lysimeter, the number of three rows and stacks were created at intervals of 1.82 meters and about 30 cm deep, and the disinfected cuttings of the variety cp69-1062 were cultivated. Two rows of reeds with a distance of 30 cm were planted in each stream and stack. Figure 1 shows the initial stages of reed growth and grass (reference plant) after planting and reed growth stages. To irrigate the boxes, 60-liter barrels were installed for each box. According to the irrigation cycle and the season, the required amount of water was given. The number of filling and emptying of these barrels in each round of irrigation was recorded for each lysimeter. The first irrigation was done up to the moisture level of the field capacity and to a depth of 30 cm. In this research, using lysimeter data, equations 1 and 2 were used to calculate capillary rise (Yang, 2007):

$$P + I + Cg = DP + RS + ET + \Delta S \tag{1}$$

$$Cg = (DP + ET) - (P + I) \tag{2}$$

where P is the daily rainfall (mm), I is the irrigation amount (mm), C_g is the capillary rise (mm), DP is the drainage water (mm) drained from the bottom of the lysimeters, RS is the surface runoff (mm), ET is the crop evapotranspiration (mm), and ΔS is the soil water content (mm) variation between two consecutive irrigation event in the root zone.

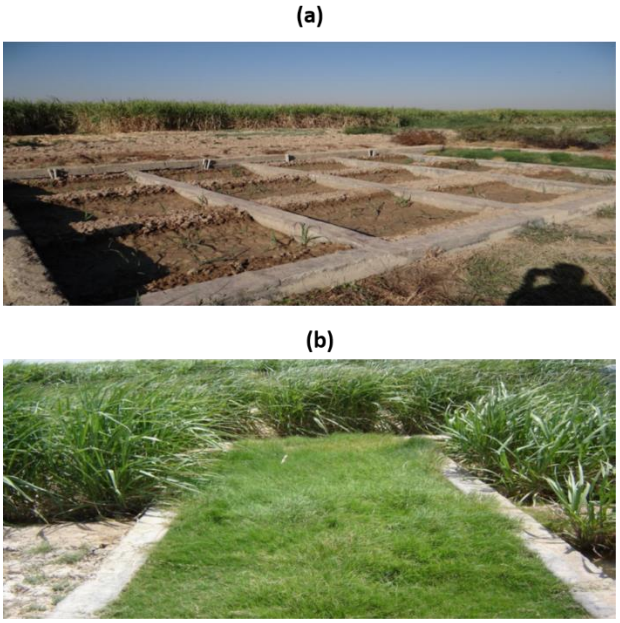

Fig. 1. (a) The stages of sugarcane cultivation in Amir Kabir agro-industry lysimeter, (b) reference plant transpiration

2.3. Description of the UPFLOW model

The one-dimensional UPFLOW model is a numerical model developed to estimate the upward movement of water and solutes from shallow groundwater to the unsaturated zone due to capillary forces under a steady state condition. It uses Darcy's law:

$$q = k(h)(\frac{dh}{dz} - 1) \tag{3}$$

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Where q is the vertical flux ($m^3m^{-2}d^{-1}$), z is the vertical co-ordinate direction (m), h is the soil matric potential (m), and k(h) is the hydraulic conductivity (md^{-1}). Solving Eq. 3 for z gives (De Laat 1980):

$$z = \int_0^h \frac{k(h)}{q + k(h)} dh \tag{4}$$

To guarantee a steady-state condition, the amount of water transported upward must be in balance with evapotranspiration. Since steady-state conditions have been applied in the calculations, the period length should not be too short (< 10 days) or too long (> one month) (Raes *et al.*, 2002; Raes and Deproost, 2003). We used 30-day averages, depending on input data availability.

The characteristics of the root system, such as density, distribution, length, etc., are highly variable under the influence of time, soil type, and depth, and therefore its accurate measurement in the field is costly and time-consuming. For these reasons, (Feddes *et al*., 1978) proposed the term maximum extraction rate (S_{max}, $m^3m^{-3}d^{-1}$) that only depends on the maximum (potential) transpiration rate (T_m, $m\ d^{-1}$) and root depth (z_r, m):

$$S_{max} = \frac{T_m}{z_r} \tag{5}$$

The S_{max} is defined as the amount of water that plant roots can extract from a certain volume of soil per unit of time.

2.4. Input parameters of UPFLOW model

In a spreadsheet type of Menu, the environmental conditions that are valid during a particular period should be specified:

a) Average evapotranspiration:

Pan evaporation (E_p, mm d^{-1}) data was used to estimate reference evapotranspiration (ET_0) as the product of the E_p data and a pan coefficient (K_p):

$$ET_0 = E_p \times K_p \tag{6}$$

The K_p in this study was variable between 58 and 78.

The 30-day mean plant evapotranspiration (ET_c) for the irrigation intervals was estimated through the water balance procedure using Eq. (1) (Dingre and Gorantiwar, 2020). Crop coefficient (K_c, dimensionless) values were computed by the relationship between ET_c and ET_0, according to Eq. (7).

$$K_c = \frac{ET_c}{ET_0} \tag{7}$$

b) Average soil water content (v/v%):

A Time Domain Reflectometry (TDR) probe was buried inside the limits of the two lysimeters at two depths of 20 and 40 cm from the soil surface. The TDR probe had dimensions of 70 mm length, 35 mm width, and 14 mm thickness, which collected and stored data once a day.

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c) Average depth of water table:

During the growing season, the depth of the shallow groundwater table was measured approximately every 2 weeks in two open pits and piezometers near the experimental field.

d) Thickness and properties of successive soil layers:

The amount of water that can flow in the soil as capillary rise depends on the physical characteristics of individual layers and soil stratification. In this study, soil parameters including soil layering were measured.

e) Water extraction pattern of the plant roots:

The crop grown in the lysimeter is sugarcane.

f) The salt content of groundwater:

The electrical conductivity of groundwater was measured using a conductivity meter (Page *et al.*, 1982).

After collecting the input data of the model, according to the UPFLOW model software, the maximum volume of the upward flow is obtained in the form of flow intensity. In this research, the data of underground water, soil, and root depth were constant during the calculations. However, the data related to evapotranspiration and root uptake rate were considered variable in each period of calculations. The capillary rise was also calculated separately for each month.

2.5. Model outputs

The outputs of the model include continuous flow of water from the water-table to the soil surface in mm/day (if any) and the average extracted water content in the soil surface when water flow does not occur. Also, this model calculates the amount of salt transferred upwards during a certain period if the underground water is salty (tons per hectare per month). In addition, it draws the degree and amount of water entering the root zone (if any) and the water profile above the saturated layer and water-table. Monthly evapotranspiration and maximum rate of water extraction by roots are also shown in Table 3 as input data of the model. The highest uptake rate is related to the upper region of the root, about 0 to 30 cm, and the lowest rate is in the lower part. In each month, the uptake rate was entered into the model according to the growth stage of the plant and potential transpiration. Due to the sensitivity of sugarcane to suffocation, the anaerobic point is considered to be 7% below the saturation point.

Table 3. Monthly evapotranspiration (ET, mm) and maximum rate of water extraction by sugarcane roots (S_{max}, mm/day)

Year	2012						2013					
Months	October	November	December	January	February	March	April	May	June	July	August	September
Monthly evapotranspiration (mm)	118.05	33.18	14.99	9.73	21.13	54.42	110.61	220.89	347.06	428.1	365.90	242.80
Maximum water extraction rate (mm/day)	0.022	0.006	0.003	0.02	0.004	0.01	0.02	0.04	0.063	0.078	.067	.044

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2.6. Model performance

The performance of UPFLOW model to predict capillary rise was assessed with coefficient of determination (R^2) (Eq. 7), mean error (ME) (Eq. 8), mean absolute error (MAE) (Eq. 9), root mean square error (RMSE) (Eq. 10), relative error (RE) (Eq. 11), index of agreement (IA) (Eq. 12), and model efficiency (EF) (Eq. 13) (Lecina *et al.*, 2003, Niazian *et al.*, 2018):

$$R^2 = \frac{\sum_{i=1}^{n}(O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2 \sum_{i=1}^{n}(P_i - \bar{P})^2}} \tag{7}$$

$$ME = \frac{1}{n}\sum_{i=1}^{n}(P_i - O_i) \tag{8}$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|O_i - P_i| \tag{9}$$

$$RMSE = \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{n} \tag{10}$$

$$RE = \frac{RSME}{\bar{O}} \times 100 \tag{11}$$

$$IA = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}[|O_i - \bar{P}| + |P_i - \bar{P}|]^2} \tag{12}$$

$$EF = \frac{\sum_{i=1}^{n}(O_i - \bar{O})^2 - \sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \tag{13}$$

Where O_i and P_i are observed and predicted values for *i*th observation, $\bar{O}$ and $\bar{P}$ are observed and predicted means and n is the number of observations. The optimum value of d and EF is unity.

3. Results and discussion

3.1. Variation of evapotranspiration and capillary rise in monthly periods of growth

Figure 2 shows the trend of capillary rise variation compared to evapotranspiration in different months of sugarcane plant growth.

The comparison of evapotranspiration and flow volume shows that the trend of variation in capillary rise is in line with the variation in evapotranspiration. If we consider the beginning in October, the value of capillary rise is 0.2 mm. With the reduction of evapotranspiration, the amount of capillary rise also decreases and becomes zero (that is, the amount of upward flow is not significant). But in March, with the increase in evapotranspiration, the amount of capillary rise starts to increase and this increase continues until July. The increase in upward flow is the same trend as the increase in evapotranspiration. In the research done by Webster (1982), the trend of capillary rise variation compared to evapotranspiration was evaluated. They stated that with the increase of evapotranspiration, the upward flow rate in the soil also increases. According to Figure 2, it can be seen that in the months of July to October, with the reduction of evapotranspiration and the vegetative growth of the plant, the capillary rise also decreases with the reduction of evapotranspiration. These results are contrary to the results of Raes and

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Deproost (2015). They showed that climate changes and variation in the growth period and plant physiology increase evapotranspiration and this variation causes more water uptake from the root zone and as a result then decreases the water content of the root zone and creates a critical potential for creating capillary rise.

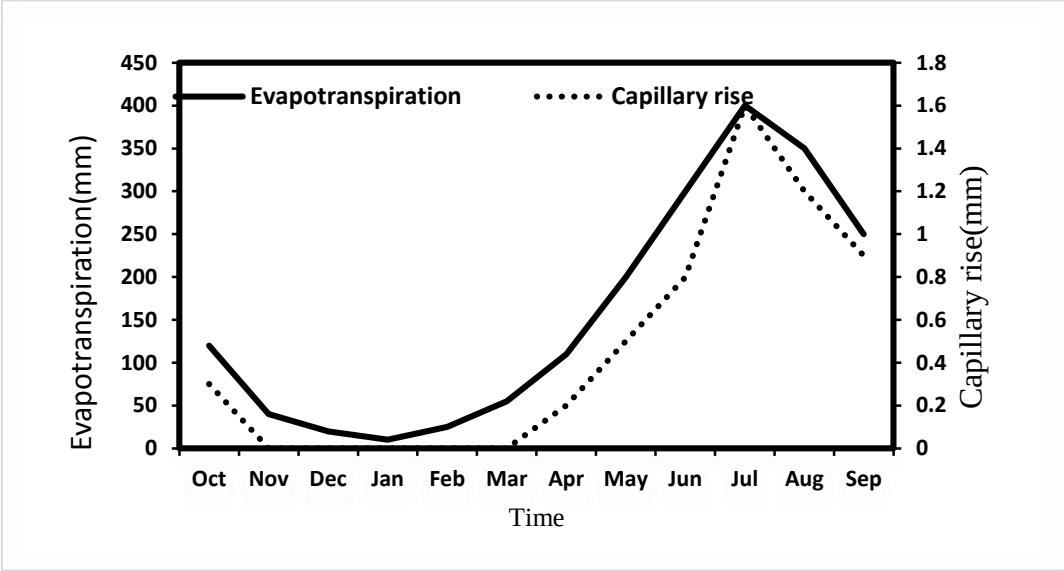

Fig. 2. Monthly variation of capillary rise and evapotranspiration with time in the crop year 2012-2013

3.2. Comparison of capillary rise variation with respect to temperature during the monthly growth period

As can be seen from Figure 3, capillary rise decreases with the decrease in temperature in October and reaches its minimum in November to January. In winter, due to the reduction of moisture variation between the surface and the depth, the upward flow reaches its lowest level and tends to zero. Capillary rise may also appear during the cold period, at a certain time when the moisture discharge reaches a critical level to create capillary. But this time is limited in cold periods and the result of the flows in the soil makes the effect of capillary rise zero. In fact, in cold periods with low evapotranspiration, the amount of upward flow in the soil is insignificant (Lacour *et al.*, 2013).

According to Figure 3, it can also be seen that the capillary rise increases with the increase in temperature in the month of April, so that the maximum capillary rise is seen at the maximum monthly temperature, vegetative growth and evapotranspiration. The results of this research are consistent with the results of (Gru¨nberger *et al*., 2011). For predict capillary rise in soil, they did a laboratory test, and investigated the effects of increasing atmospheric temperature on the rate of capillary rise. The result of their observations showed that in cases where the soil surface is without vegetation in the vicinity of a shallow water-table, the temperature increases the capillary rise to some extent and then it decreases. But in cases where the soil surface is irrigated, the increase in temperature will increase capillary rise in the soil by affecting evapotranspiration and increasing plant growth.

3.3. Simulation of capillary rise in UPFLOW model

According to field investigations, the soil profile has a clay loam texture. The thickness of this layer was 2 meters and its average hydraulic conductivity was considered to be 0.35 meters per

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day. According to the measurements, the depth of the underground water in the area has been measured between 1.75 and 2.5 meters.

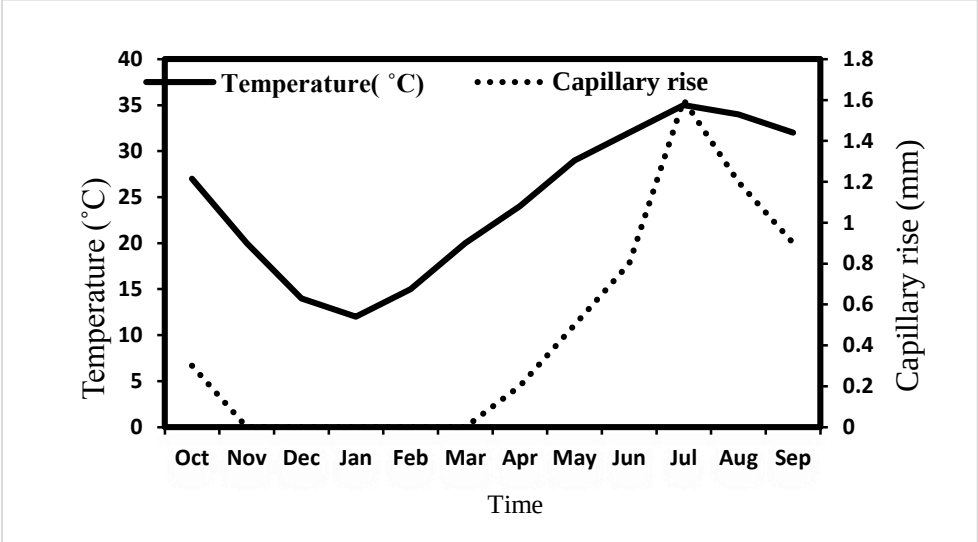

Fig. 3. Variation of capillary rise and temperature with time in the crop year 2012-2013

According to the natural conditions, the depth of underground water in the lysimeter was considered to be at the lowest level of the drainage pipe at two meters from the ground surface. In order to calculate the volume of salt raised due to upward flow, the electrical conductivity of underground water was entered into the software. In the definition of this model, the groundwater depth must be at least one meter below the effective root depth. The annual average electrical conductivity of underground water in the crop year of 2013-2014 was reported to be about 4.3 millisiemens/cm.

According to Figure 4, it can be seen that from October to January, the amount of evapotranspiration decreases and reaches its minimum in January. In the months when evapotranspiration is low, the capillary rise simulated by the model is close to the evapotranspiration chart, and in January, the amount of evapotranspiration is equal to the capillary rise. According to Raes (2000), the maximum capillary rise is equal to evapotranspiration and will not exceed it. These researchers showed that the maximum upward flow cannot exceed evapotranspiration.

As can be seen in Figure 4, from January to March, the amount of simulated evapotranspiration and capillary rise increases with a low gradient. But from April onwards, with the warming of the air and the intensification of plant growth, the gradient of the simulated evapotranspiration graph also increases, and in each one-month period, the amount of evapotranspiration increases significantly compared to the previous month. With the increase of evapotranspiration from April to July, the amount of capillary rise increases, but the gradient of its increase is not the same as the steep gradient of the evapotranspiration graph, and it has a relatively mild gradient. These variations are consistent with the study of Piotr (2006). Comparison of Figure 4 with Figure 2 shows that the capillary rise simulation of this model matches the observed values.

According to Figure 5, the trend of capillary rise variation is parallel to the trend of the rate of water extraction by sugarcane roots. The minimum upward flows occur at the minimum uptake rate and the maximum upward flows also occurs at the maximum uptake rate. In a study

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conducted by (Feddes *et al*., 1978) in connection with the simulation of water uptake rate by roots, it was observed that the increase of uptake rate in the period of time causes a decrease in the potential of the soil surface.

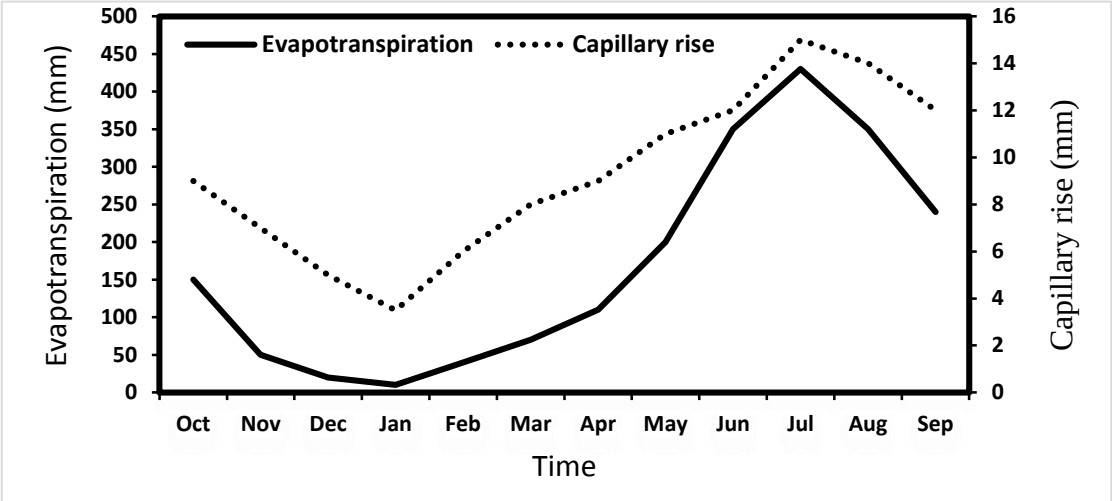

Fig. 4. Simulation of evapotranspiration and capillary rise with time using the UPFLOW model

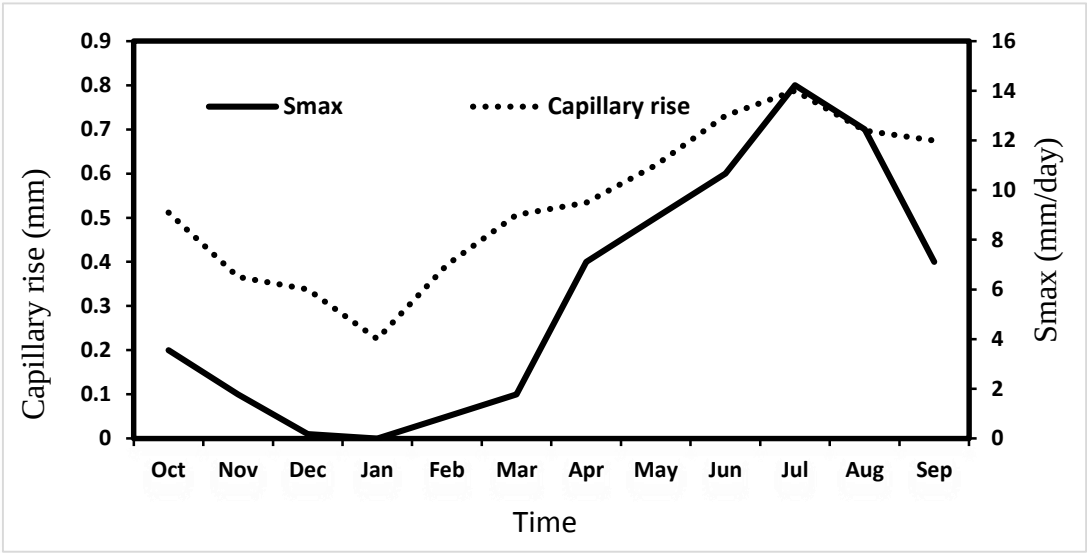

Fig. 5. Simulation of water extraction rate by root and capillary rise with time using UPFLOW model

Therefore, the increase in water uptake causes more water to be extracted from the soil surface and the root zone and creates a potential gradient between the water-table and the soil surface and changes the direction of the flow in the soil. When the upward flow occurs, depending on the quality of the underground water, it carries some amount of salt with it upwards. Based on the simulation of the UPFLOW model, in this study, the largest volume of salt is transported to the sugarcane root area in July, about 1 ton per hectare per month.

3.4. Statistical indicators of simulation performance

Table 4 shows the Statistical indicators of simulation performance of the UPFLOW model in Amirkabir agro-industry. According to Table 4, it can be seen that the coefficient of

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determination (R^2), mean error (ME), mean absolute error (MAE) and root mean square error (RMSE) are 0.23, 8.7, 8.7 and 9.1 respectively.

Table 4. Validation indices of UPFLOW model compared to observed data

Index	R^2	ME	MAE	RMSE	RE	EF	IA(d)
Value	0.23	8.71	8.71	9.10	180.5	-136.4	-6.25

The value of the correlation coefficient indicates a low correlation between the data. The average value of the absolute value of the error was also calculated equal to the average error, which shows the magnitude of all the estimated values from real observations (Figure 6).

The relatively high value of root mean square error also indicates the error of the model in estimating capillary rise in the studied area. According to Table 4, the efficiency index of the model (EF) was calculated as -136. The negativity of this value and the fact that this value is out of the range between 0 and 100 indicate that the model outputs do not match with the real data. Also, Wilmot's index (d) was calculated as -6.25. The negativity and distance of this index from its standard limit indicates the inappropriate efficiency of the model and the low accuracy of the model.

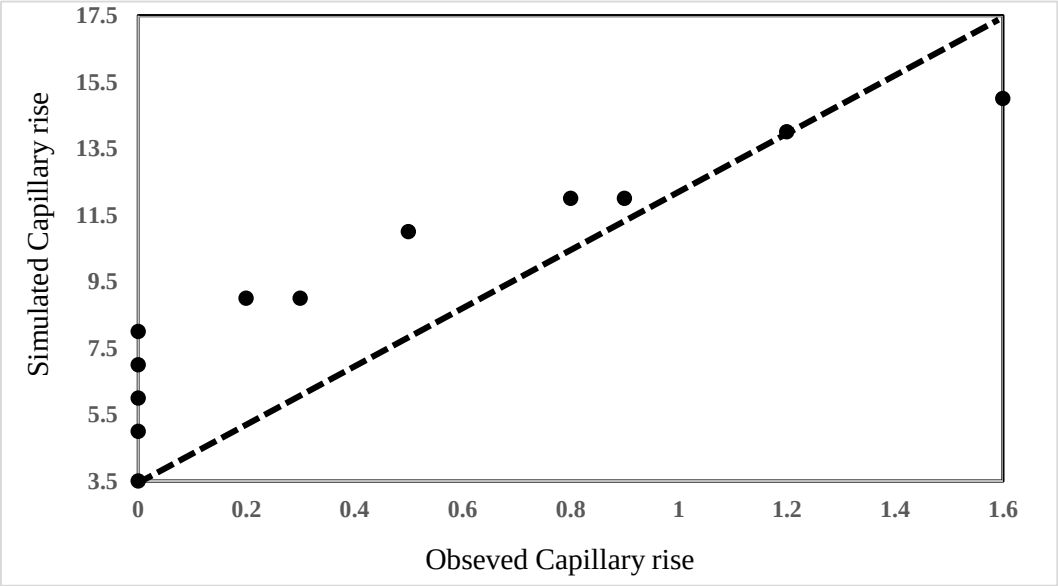

Fig. 6. Distribution of simulated capillary rise values around the 1:1 line

4. Conclusion

The results of this research showed that capillary rise increases with increasing temperature and vegetative growth of sugarcane. But according to the irrigation and drainage system, climatic conditions and physical and chemical characteristics of water and soil in Amirkabir agro-industries, capillary rise was less than 2 mm. capillary rise trend variation simulated by the UPFLOW model was in accordance with the values measured by the lysimeter. Although the statistical indicators show the inappropriate efficiency of this model in the agricultural system in South Khuzestan. Comparing the results of this research with the results of other researchers confirms that the effectiveness of this model depends on the place and location of the research. In the new edition of this model, some defects such as the maximum evaporation potential have been removed. But there are still errors in the rise capillary simulation. Therefore, it is suggested

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that this model be evaluated in different weather conditions, different soils, cropping systems and different plants.

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